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ENHANCING BENEFITS OF NUCLEAR ENERGY TECHNOLOGY INNOVATION THROUGH COOPERATION AMONG COUNTRIES: FINAL REPORT OF THE INPRO COLLABORATIVE PROJECT SYNERGIES

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IAEA NUCLEAR ENERGY SERIES No. NF-T-4.9

ENHANCING BENEFITS OF NUCLEAR ENERGY TECHNOLOGY INNOVATION THROUGH COOPERATION AMONG COUNTRIES: FINAL REPORT OF THE INPRO COLLABORATIVE PROJECT SYNERGIES

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was established in 2000 to help to ensure that nuclear energy is available to contribute to meeting the energy needs of the 21st century in a sustainable manner. INPRO focuses on key issues of global sustainability of nuclear energy with the aim of assisting in the development of long term nuclear energy strategies. INPRO Task 1, on global scenarios, analyses regional and global nuclear energy scenarios to achieve a global vision of how nuclear energy could be sustainable within the present century.

Several collaborative projects were established by INPRO members within Task 1. The INPRO collaborative project Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS) developed a framework for dynamic assessment of current and future nuclear energy systems with regard to sustainability.

This publication presents the results of the follow-up collaborative project Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES). This collaborative project was jointly implemented in 2012–2015 by Algeria, Argentina, Armenia, Belgium, Bulgaria, Canada, China, France, India, Indonesia, Israel, Italy, Japan, the Republic of Korea, Malaysia, Pakistan, Poland, Romania, the Russian Federation, Spain, Ukraine, the United States of America, Viet Nam and the OECD Nuclear Energy Agency as participants or observers.

The INPRO collaborative project SYNERGIES applied and amended the analytical framework developed in GAINS to model more specifically the various forms of collaboration among countries, assess benefits and issues relevant for collaboration, and identify those collaborative scenarios and architectures that ensure a 'win–win' strategy for both suppliers and users of peaceful nuclear energy technologies. The results of the study have increased understanding of how best to enhance sustainability of nuclear energy systems in the 21st century.

The IAEA officers responsible for this publication were V. Kuznetsov and G. Fesenko of the Division of Nuclear Power.

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1. INTRODUCTION

1.1. BACKGROUND

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) provides a mechanism for ensuring availability and contribution of nuclear energy to sustainably meet the energy demands of the 21st century.[1] To achieve this, INPRO brings together nuclear technology holders and users to consider jointly international and national actions that would result in required innovations in nuclear reactors, fuel cycles or institutional approaches. INPRO Task 1: Global Scenarios develops and analyses nuclear energy scenarios in regional or global environment for achieving global vision of nuclear energy sustainability in the current century [1.1]. As reported in Ref. [1.1] (see also Refs [1.2–1.4]):

> "Existing nuclear energy systems, which are almost entirely based on thermal reactors operating in a once-through cycle, will continue to be the main contributor to nuclear energy production for at least several more decades. However, results of multiple national and international studies show that the criteria for developing sustainable nuclear energy cannot be achieved without major innovations in reactor and nuclear fuel cycle technologies.
>
> "New reactors, nuclear fuels and fuel cycle technologies are under development and demonstration worldwide. Combining different reactor types and associated fuel chains creates a multiplicity of nuclear energy system arrangements potentially contributing to global sustainability of nuclear energy. In this, cooperation among countries having different policy regarding fuel cycle back end would be essential to bring sustainability benefits from innovations in technology to all interested users."

In accordance with other IAEA activities, INPRO provides integrated services to Member States considering embarking upon or expanding their nuclear energy programmes. The specific target is to develop a better understanding of how nuclear energy sustainability could be enhanced. An internationally verified analytical framework for analysing transition scenarios to nuclear energy systems (NESs) of enhanced sustainability (referred to as the framework) has been developed by INPRO. This framework has been used in several case studies performed by the project participants [1.1, 1.5]. Reference [1.1] reports that:

> "The economic studies carried out by INPRO have shown that investments in Research, Design & Demonstration (RD&D) for innovative technologies, such as fast reactors and a closed nuclear fuel cycle, are huge and provide reasonable pay-back times only in the case of a foreseen large scale deployment of such technologies. Not all of the countries interested in nuclear energy could and would afford such investments. Then, benefits associated with innovative technologies can be amplified, and may also be brought to many interested users through mutually beneficial cooperation among countries in fuel cycle back end."

To take this into account, the INPRO collaborative project on Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS), conducted in 2008–2011, has introduced a heterogeneous world model to reflect upon different policies of different countries with respect to the nuclear fuel cycle and, specifically, its back end. This model enables analysing options for cooperation among countries in a nuclear fuel cycle (see Appendix III) [1.1, 1.2]. The heterogeneous model may involve certain degrees of cooperation between non-geographical groups of countries (synergistic case) or it may involve no cooperation (non-synergistic case). The heterogeneous world model is therefore a part of the framework used to evaluate the various strategies of nuclear fuel cycle development as pursued by different countries and to define a potential for mutually beneficial cooperation [1.1].

Synergies among the various existing and innovative nuclear technologies and options to expand their positive impact through collaboration among countries in back end of the nuclear fuel cycle were the subject of the INPRO collaborative project on Synergistic Nuclear Energy Regional Group Interactions Evaluated

[1] For further information, see the INPRO web site at www.iaea.org/INPRO/CPs/index.html

for Sustainability (SYNERGIES) [1.1], the outputs of which are presented in this publication. Conducted in 2012–2015, SYNERGIES involved experts from Algeria, Argentina, Armenia, Belgium, Bulgaria, Canada, China, France, India, Indonesia, Israel, Italy, Japan, the Republic of Korea, Malaysia, the OECD Nuclear Energy Agency, Pakistan, Romania, Poland, the Russian Federation, Spain, Ukraine, the United States of America and Viet Nam contributing as participants or observers. The project modelled and examined the various synergies among nuclear technologies and forms of collaboration among nuclear technology suppliers and users in order to identify mutually beneficial strategies for working together to promote the sustainable expansion of nuclear energy worldwide and also to identify the corresponding driving forces and possible impediments involved in achieving globally sustainable NESs.

The GAINS and SYNERGIES collaborative projects are important steps in realizing the sustainability goals of NESs and in providing a pathway for sustainable nuclear energy development throughout this century. To facilitate Member States strategic nuclear energy planning, INPRO Task 1: Global Scenarios has defined several options for enhanced nuclear energy sustainability, starting systems based on once through nuclear fuel cycle and leading to advanced systems in which all actinides are recycled.

Following GAINS and SYNERGIES, the collaborative project Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems (ROADMAPS) would use the defined sustainability options to develop a structured approach for achieving globally sustainable nuclear energy by developing a template for documenting actions, scope of work and timeframes by particular stakeholders for specific collaborative efforts. The roadmap template will indicate, inter alia, where savings in time, effort and resources could be achieved by countries through international collaboration.

1.2. OBJECTIVE

The objective of this publication is to present the results, findings and conclusions of the INPRO collaborative project SYNERGIES. The objective of the SYNERGIES collaborative project, implemented in 2012–2015, was to identify and evaluate mutually beneficial forms of collaboration, and the driving forces and possible impediments involved in achieving globally sustainable NESs, as determined by the participants of the SYNERGIES project. The associate analyses were accomplished in part by applying and enhancing the analytical framework (codes, databases and NES deployment scenarios) developed in GAINS and in part by making use of national assessment studies. The focus was on forms of collaboration and synergies between technologies that could ensure a ‘win-win’ strategy for both holders and users of nuclear technology.

The specific objective was to illustrate and identify short term and medium term options for collaboration capable of facilitating the transition to long term sustainability. It is recognized that such collaboration should provide benefits in economics, security of supply, resource allocation, infrastructure requirements, radioactive waste management, and other key areas defined by the INPRO methodology for NES assessment [1.6].

The target audience for this publication includes decision makers such as senior experts working in nuclear power programme planning, senior officers of national ministries and regulatory bodies responsible for nuclear technology development and international cooperation programmes, and the research and technical organizations that provide technical advice to the decision making process. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.3. SCOPE

The SYNERGIES collaborative project activities were organized under four major tasks, as follows:

1.3.1. Task 1: Evaluation of synergistic collaborative scenarios of fuel cycle infrastructure development

For this task, case studies were performed by project participants highlighting synergies among the various nuclear technologies and strategies of synergistic collaborations among countries in the fuel cycle towards sustainable regional and global NESs.

1.3.2. Task 2: Evaluation of additional options for nuclear energy systems with thermal and fast reactors

This task extended the heterogeneous and homogeneous global and regional NES analyses to consider additional deployment scenarios not considered in the previous INPRO studies and projects [1.2, 1.3, 1.7].

1.3.3. Task 3: Evaluation of options for minor actinide management

This task elaborated on previously considered [1.2, 1.3] and new options for minor actinide management with respect to both, developing nuclear energy programmes and nuclear phase out scenarios. Some case studies for this task provided summaries of selected national regional studies carried out in Member States in recent years.

1.3.4. Task 4: Elaboration of key indicators specific for synergistic collaboration, including economic assessment methods

This task extended the analytical framework developed in the GAINS collaborative project [1.2]. The activities performed under this task included:

(a) Review and revision of the key indicator set developed in the GAINS project [1.2]. The results of this review, conducted based on the case studies performed in SYNERGIES, are presented in Appendix I. They confirm the validity of the metrics developed in GAINS with only minor changes introduced by the participants of SYNERGIES.
(b) Development of an updateable database of best estimate cost data for fuel cycle stages and nuclear reactors, presented in Appendix II. This database, developed on the basis of multiple publications in open literature, provides ranges and best estimate values for the costs and also includes the economy of scale data, where available. It was used in a number of case studies carried out within the SYNERGIES project.

The SYNERGIES case studies were structured along the following four scenario families [1.1]:

(1) Business as usual scenarios consisting of once through fuel cycle and mono-recycling of U/Pu in thermal spectrum reactors (Scenario family A);
(2) Scenarios with the introduction of a number of fast reactors to support multi-recycling of Pu in LWRs and fast reactors (Scenario family B);
(3) Fast reactor centred scenarios enveloping scenarios with reprocessing of thermal reactor fuel to enable noticeable growth rate of fast reactor capacity (Scenario family C);
(4) Scenarios of transition to Th/^{233}U fuel cycle and scenarios with alternative U/Pu/Th fuel cycles (Scenario family D).

Summaries of 27 SYNERGIES case studies structured according to a common format are presented in Section 3, along with the considered scenario families. They are structured according to the selected scenario families. Full descriptions of the case studies documenting the analyses performed by Member States and the IAEA are provided on the CD-ROM accompanying this publication. Table 3.1, in Section 3, also presents the correlation between case studies, scenario families and projects tasks.

Compared to GAINS, SYNERGIES considered within its scenario studies a broader range of technologies and fuel cycle options, including:

— Uranium oxide and mixed oxide fuelled light water reactors (LWRs) and advanced LWRs operated in a once through and closed nuclear fuel cycle, with single and multiple plutonium recycling. Advanced LWRs with supercritical coolant parameters were also considered.
— Heavy water reactors (HWRs) with uranium based fuel load, including that based on reprocessed uranium from LWRs. The use of HWRs for transmutation of americum from LWR fuels, was also considered.
— Small and medium sized and high temperature reactors.
— Advanced HWRs and LWRs with a uranium–thorium fuel load operated in a once through fuel cycle with ^{233}U breeding and burning in situ.

— Sodium cooled fast reactors with mixed oxide and metallic uranium–plutonium or transuranics based fuel with different breeding ratios operating in a closed fuel cycle with the initial loads obtained from reprocessed LWR spent fuel.
— Sodium cooled fast reactors with mixed oxide and metallic uranium–plutonium based core fuel with thorium blankets operated in closed uranium–plutonium/^{233}U–thorium fuel cycles.
— Lead cooled fast reactors with the initial load based on enriched uranium, operated in a closed fuel cycle with recycling of their own fuel.
— Dedicated sodium cooled fast reactors as transuranic burners.
— Accelerator driven systems for minor actinide transmutation.

In its scenario studies, SYNERGIES considered a variety of scenario models and options of cooperation among countries, including:

— Heterogeneous and homogeneous world models (previously considered in GAINS);
— Heterogeneous regional models;
— Cooperation among countries holding different nuclear power plant technologies;
— Cooperation among technology holder and technology user countries, including outsourcing of fuel cycle functions to international fuel cycle vendors;
— Regional approaches to interim spent nuclear fuel storages;
— International approaches to cooperation in the fuel cycle back end.

Drivers and impediments for collaboration among countries were assessed in some of the case studies done by project participants as well as through discussions at SYNERGIES technical meetings and a dedicated INPRO Dialogue Forum 4, on drivers and impediments for regional cooperation on the way to sustainable nuclear energy systems [1.4] (see Appendix IV for a summary of the findings).

1.4. STRUCTURE

Section 1 presents the background and specifies the objective of the SYNERGIES collaborative project. It outlines the project scope, introduces the structure and provides explanations of the specific terms used in this and the previous studies of the INPRO Task 1: Global Scenarios. Section 2 discusses sustainability aspects and options of nuclear energy development scenarios and possible solution of sustainability issues. It describes selected storylines as a basis for the case studies performed within the collaborative project based on the results of the previous studies and taking into account consolidated option of the participants. Section 3 presents summaries of 27 case studies carried out by Member States grouped to the following sections according to the family of reactor and fuel cycle types used in the analysis (Scenario families A–D). The studies include a description of the assumptions, input parameters and outputs as well as the analysis of the results and main conclusion of the case study. The section provides the main results from the studies and conclusions with regard to scenario families. Section 4 discusses near and medium term actions needed to enable longer term sustainability of global nuclear energy. The actions are grouped into several areas, including technology development, infrastructure development and institutional developments. Technology development is primarily needed to advance innovative technologies that are not yet available at a technical maturity level to support industrial scale deployment. Infrastructure development includes expanded deployment of current and new technologies and facilities. Institutional developments are used broadly here and cover establishment of personnel training, regulatory agencies, trade agreements and legal authority, among others. The section also summarizes drivers and impediments for collaboration among countries. Section 5 summarizes the main finding of the studies and provides conclusions and the experts' recommendations on synergies in technology as well as synergistic collaboration between countries.

Appendix I collects key indicators for collaborative NES scenario assessment on sustainability used in the case studies. Appendix II describes economic assessment data, methods and tools. Appendix III provides a short description of the GAINS approach. Appendix IV summarizes major findings of the fourth INPRO Dialogue Forum, on drivers and impediments for regional cooperation on the way to sustainable nuclear energy systems [1.4].

Appendix V introduces concept of options for enhanced nuclear energy sustainability. Full reports of these studies are included on the CD-ROM accompanying this publication.

1.5. EXPLANATION OF THE SPECIFIC TERMS USED

1.5.1. Nuclear energy system

According to the definition used by the INPRO methodology [1.6], an NES comprises the complete spectrum of nuclear facilities and associated institutional measures. Nuclear facilities include facilities for mining and milling, processing and enrichment of uranium or thorium, manufacturing of nuclear fuel, production (of electricity or other energy related products, e.g. steam or hydrogen), reprocessing of nuclear fuel (if a closed nuclear fuel cycle is used), and facilities for related materials management activities, including storage, transport and waste management.

1.5.2. Sustainable nuclear energy system

The United Nations concept of sustainable development includes economic, environmental, social and institutional dimensions [1.8]. When mapped against these dimensions, the unique characteristics of nuclear energy result in specific subject areas in the INPRO methodology for NES assessment [1.6]: economics, safety of nuclear installations, waste management, proliferation resistance, environment and infrastructure. Enhanced sustainability in one or more of these subject areas may be achieved through improvements in technologies or changes in policies and institutions. Synergistic approaches that would combine various NES options deployed within different countries into a globally more sustainable NES, would and could be beneficial, although the drivers towards such development should primarily be induced by the current nuclear technology holders.

1.5.3. Globally sustainable nuclear energy system

A globally sustainable NES is a system that is safe, secure, economical and publicly acceptable and that maximizes the usable energy produced from natural resources while minimizing the waste resulting from the system. Achieving long term sustainability of the global NES is considered as a response to major challenges related to public acceptability, economics, technological development and some other issues. From a global sustainability standpoint some sustainability criteria, such as those related to resource availability and waste management could be better achieved through cooperation among countries on a regional or global level. In this sense, the wording globally sustainable NES will be used to refer to the combination of national systems and collaborative efforts that effectively contribute to sustainability on a global level.

1.5.4. GAINS analytical framework

The INPRO collaborative project GAINS, conducted in 2008–2011, developed an international analytical framework to analyse scenarios of transition to NESs of enhanced sustainability and applied it in sample analyses [1.2]. This framework, referred to as the GAINS analytical framework, includes [1.1, 1.4]:

— A common methodological approach, including basic principles, assumptions, and boundary conditions;
— Scenarios for long term nuclear power evolution based on IAEA Member States' high and low estimates for nuclear power demand until 2050, and trend forecasts to 2100 based on projections of international energy organizations;
— A heterogeneous global model to capture countries' different policies regarding the back end of the nuclear fuel cycle;
— Metrics and tools to assess the sustainability of scenarios for a dynamic NES, including a set of key indicators and evaluation parameters;

— An international database of best estimate characteristics of existing and future innovative nuclear reactors and associated nuclear fuel cycles for material flow analysis, which expands upon other IAEA databases and takes into account different preferences of Member States;
— Findings from analyses of scenarios of a transition from present nuclear reactors and fuel cycles to future NES architectures with innovative technological solutions.

The framework is included in the integrated services provided by the IAEA to Member States considering embarking upon or expanding their nuclear energy programmes.

1.5.5. Synergies, synergies in technology and synergies in collaboration among countries

Synergies within the context of NESs are all actions that a country or a group of countries undertake to facilitate (i.e. enable, accelerate and optimize) the deployment of an NES aiming at enhancing its sustainability. Synergies are actions that make optimal use of a combination of technologies (i.e. synergies of intranuclear options) within the perimeter of a national or regional NES, as well as those that demand more increased cooperation among countries, each with their own NES, but where the cooperation brings benefits in achieving each country’s or collective sustainability objectives of an NES. The following two major types of synergies are distinguished in this publication:

— Synergies in technology: synergies among technologies with certain complementarity between fuel cycles of different reactors on a purely technical level.
— Synergies in collaboration: synergistic collaboration among countries with different policies regarding nuclear fuel cycle based on certain arrangements and aimed at bringing the benefits of innovation to all interested users.

1.5.6. Heterogeneous global model

Most studies on the future of nuclear energy are based on a homogeneous global model, which suggests a world rapidly converging towards global solutions for economic, social and environmental challenges. This model emphasizes the opportunities facilitating creation of the regional and global nuclear architecture, such as unification of reactor fleets and associated technologies, infrastructure sharing, multinational fuel cycle centres and innovative approaches to financing and licensing, among other things. However, it does not take into account the barriers to cooperation between different parts of the world, or national preferences and capabilities [1.5].

To complement this model, the GAINS project developed a heterogeneous model based on grouping countries with similar fuel cycle strategies. This model can facilitate a more realistic analysis of transition scenarios towards a global architecture of innovative NESs. It can also illustrate the global benefits that would result from some countries introducing innovative nuclear technologies, which would limit the exposure of the majority of countries to the financial risks and other burdens associated with the development and deployment of these technologies [1.2].

The heterogeneous world model developed by GAINS organizes countries into groups according to their strategies of spent nuclear fuel management [1.2, 1.5]:

— Group NG1 countries pursue a general strategy to recycle spent nuclear fuel and plan to build, operate and manage spent fuel recycling facilities and permanent geological disposal facilities for highly radioactive waste.
— Group NG2 countries follow a strategy either to directly dispose spent nuclear fuel or send it abroad for reprocessing. These countries plan to build, operate and manage permanent geological disposal facilities for highly radioactive waste (either as spent fuel or reprocessing waste) but may work synergistically with countries from another group to recycle fuel.
— Group NG3 countries have a general strategy for the front end of the fuel cycle — to acquire fresh fuel from abroad and send spent fuel abroad for either recycling or disposal — but have not developed plans to build, operate, or manage spent fuel recycling facilities or permanent.

The heterogeneous model may involve some degree of cooperation between groups in nuclear fuel cycle (synergistic case), or it may not involve any cooperation (non-synergistic case) [1.2, 1.5].

1.5.7. Metrics for scenario analysis and assessment

The GAINS collaborative project has developed its own metrics to assess transition scenarios to sustainable NESs, including those providing for synergistic collaboration among countries in nuclear fuel cycle in the heterogeneous global model [1.2]. The GAINS metrics represented by a set of ten key indicators [1.2, 1.6][2] and evaluation parameters build upon the INPRO methodology for NES assessment [1.6], but in most cases does not duplicate it (see Table 2.1, in Section 2.3). It is narrower and focuses on the areas that are important for scenario analysis (i.e. can be assessed through material flow analysis and associated economic analysis). The major areas are resource availability and production of waste, the associate power capacity curves for nuclear reactors involved, radioactivity and radiotoxicity of waste, but also demand in fuel cycle services and costs and the required investments. Such important areas as safety, physical protection and proliferation resistance are either not touched or only marginally touched upon by the GAINS metrics.

The relationship between the United Nations concept of sustainable development, the INPRO methodology and the GAINS analytical framework is discussed in more detail in Sections 2.1–2.5.

1.5.8. Short, medium and long term

For the purpose of the SYNERGIES studies, the following definitions were used:

— Short term: 2015–2030.
— Medium term: 2030–2050.
— Long term: 2050–2100.

1.5.9. Security

The term security as used throughout the publication is consistent with the IAEA definition of the "prevention and detection of, and response to, theft, *sabotage*, unauthorized access, illegal transfer or other *malicious* acts involving *nuclear material*, other *radioactive material* or their associated *facilities*."[3]

REFERENCES TO SECTION 1

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[1.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability: Final Report of the INPRO Collaborative Project GAINS, IAEA Nuclear Energy Series No. NP-T-1.14, IAEA, Vienna (2013).

[1.3] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Energy Development in the 21st Century: Global Scenarios and Regional Trends, IAEA Nuclear Energy Series No. NP-T-1.8, IAEA, Vienna (2010).

[1.4] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Dialogue Forum 4: Drivers and Impediments for Regional Cooperation on the Way to Sustainable Nuclear Energy Systems (Vienna, 30 July–3 August 2012), www.iaea.org/INPRO/4th_Dialogue_Forum/index.html

[1.5] INTERNATIONAL ATOMIC ENERGY AGENCY, Analytical Framework for Analysis and Assessment of Transition Scenarios to Sustainable Nuclear Energy Systems, IAEA, Vienna (2014).

[2] The concept of key indicators was introduced in the INPRO methodology [1.6] to offer a distinct capability for capturing the essence of a given subject area in NES assessment and to provide the means to establish targets for improvement in a specific area to be reached via improving technical or infrastructural characteristics of an NES. This concept allows introducing specific targets where NES performance would surpass the acceptance limits defined in the INPRO methodology. When developing its metrics, GAINS has used this concept by applying it to scenario analysis for NESs [1.2].

[3] See www.iaea.org/resources/safety-standards/safety-glossary

[1.6] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems: INPRO Manual — Overview of the Methodology, IAEA-TECDOC-1575 Rev. 1, IAEA, Vienna (2008).
[1.7] INTERNATIONAL ATOMIC ENERGY AGENCY, Role of Thorium to Supplement Fuel Cycles of Future Nuclear Energy Systems, IAEA Nuclear Energy Series No. NF-T-2.4, IAEA, Vienna (2011).
[1.8] BRUNDTLAND COMMISSION, Report of the World Commission on Environment and Development: Our Common Future, Oxford University Press, Oxford (1987).

2. SYNERGIES STORYLINES AND SCENARIO FAMILIES

2.1. BASIC FEATURES AND SUSTAINABILITY POTENTIAL OF NUCLEAR ENERGY

Whatever the sociopolitical context for nuclear energy is at present, or may become in the future, it is important to recognize certain basic features of nuclear energy that define or even drive nuclear energy systems (NESs) to serve a sustainable energy future locally, regionally or globally. Nuclear energy holds 10^6 more energy per unit mass of fuel (uranium or plutonium or thorium; in general, per unit mass of fertile/fissile material) than any fossil fuel and even more so for renewable energy resources. This very high energy density means that very little material needs to be included in the supply chain towards nuclear power plants compared to these other energy generating technologies and that, in principle, from a technical and logistics perspective, this very small amount of mass to be handled in the fuel cycle is a very big advantage, for example shipment of fuel materials in the nuclear fuel cycle are limited and of small size per TW·h and thus virtually represent zero environmental impact overall.

Nuclear energy is very capital intensive, requiring a high capital investment. However, as fuel costs are very low, the operational expenses for nuclear energy are also relatively low. This high capital intensity spreads over the whole period from initiating plans towards a nuclear plant, through the licensing process and the construction up to commercial operation, which altogether typically takes 15 years, resulting in additional expenses related to loan interest. This hints towards the economies of scale (or, alternatively, the economies of numbers when considering modular designs) for nuclear power plants to reduce the fixed costs per TW·h later on generated as much as possible. While the absolute capital investment becomes very high, and sometimes even beyond the abilities of smaller electricity utilities or investors, the high predictability and the virtually absent cost volatility in nuclear generation render nuclear energy very attractive, especially in view of the total independence of carbon tax impacts, when applicable.

To ensure faster return of large initial investments, nuclear power plants ideally operate at a constant load factor to deliver baseload electricity which, combined with the very low cost per TW·h generated, explains their typical baseload merit order in (national) electricity grids. Many members of the Organisation for Economic Co-operation and Development have well developed, interconnected electricity grids. Besides being well suited to large capacity baseload operation, these well interconnected grids have nowadays allowed, to a better degree than in other less interconnected regions, to incorporate a growing share of time stochastic (or intermittent) renewable energy resources, given important transmission capacity exists between (sub)regions within such interconnected grids [2.1–2.3].

Nuclear material only accounts only for a few per cent (typically 5%) in the overall generating cost for nuclear energy, and this indicates a high natural resource price independency strengthened by a natural uranium distribution across the world being different than the typical fossil fuel resource distributions [2.4]. All this contributes to a higher energy independency for those countries that would a significant nuclear energy fraction in their energy balance. In addition, some nuclear fuel cycle options involving reprocessing and recycling of uranium and plutonium further increase the available fissile resource and energy independence, while significantly reducing the natural uranium needs per TW·h. The present day nuclear power plants are being increasingly designed to operate with different fuel types, for example uranium oxide (UOX) and mixed oxide (MOX). Longer term innovative nuclear power plant designs, the so called Generation IV designs, often rely on fast neutron spectrum, adding additional fuel cycle flexibility potential. Next, the international nuclear fuel cycle, especially in the front end, has established itself as a competitive environment securing multiple supplier channels to many nuclear power plant operators. As such, in principle, nuclear fuel supply for nuclear energy is not an impediment to nuclear energy deployment, though local and regional options to secure such nuclear fuel supply may differ.

Nuclear energy, as any other industrial activity, produces waste which needs to be managed responsibly. The amount of nuclear waste is very small per TW·h compared to the amount of waste produced by many other industries, especially fossil fuel based energy generation technologies. However, the fact that nuclear waste remains radioactive and radiotoxic over sometimes very long periods reaching hundreds of thousands or even millions of years combined with a sociopolitical ‘fear’ of radioactivity may result in a disproportionate ‘fear factor’ associated with nuclear waste. This fear stems from the fact that, different from other factors hazardous to human health and environment, radioactivity is intangible and cannot be detected directly by common senses.[1] Long or very long lasting nature of radioactivity also complicates proving long term waste management solutions. For these reasons a virtually 'stand-still' situation with regard to deployment of any ultimate waste management solution proposed in the course of the previous four decades. This disproportionate fear of nuclear waste, despite the known waste management solutions, including those incorporating retrievability of storage facilities and repositories, has delayed full deployment of the ultimate waste management solution (i.e. geological disposal). In turn, this has impacted the deployment potential of nuclear energy, as public at large hesitates embracing nuclear energy for mostly this reason. Only about 5% of the used fuel discharged from nuclear power plants ultimately becomes waste to be disposed of, while a much larger part of used fuel is actually recyclable in today's light water reactors (LWRs) (and heavy water reactors, HWRs) and increasingly in fast neutron spectrum reactors of the Generation IV type.

The physicochemical characteristics of the ultimate waste coming from the oxide fuel used in today's nuclear power plants and envisaged to be used to meet the bulk of the projected nuclear energy demand within the present century fit well to final disposal in the reducing geological disposal conditions. Most, if not all, of the geological disposal solutions presently under investigation are of reducing nature (clay, salt and rock), under which the engineering barriers put in place would result in a virtually zero mobility of the radioactive content in ultimate nuclear waste and, therefore, in a very low, almost insignificant, radiological risk from such geological disposal sites. This would apply for sure when the ultimate waste stems from the reprocessing cycles where the bulk material, being uranium (~94%) and plutonium (~1%), are removed from the vitrified ultimate waste, which then contains only fission and activation products and minor actinides.

Further enhancement of the ultimate waste management could be considered by deploying separation/partitioning and transmutation technologies envisaging the separation of some, if not all, of the minor actinides from the ultimate waste stream in order to transmute them in (mostly) fast neutron spectrum reactors in view of reducing their amount and their longevity, potentially resulting in a reduction of the decay heat and radiotoxicity of the then to be disposed ultimate waste. A variety of international and national studies [2.5] performed during the last few decades have shown that, in comparison to an all plutonium multi-recycling management scheme in fast reactors, partitioning and transmutation of all minor actinides can reduce the decay heat, resulting in a reduction of the high level waste section of a repository footprint by a factor up to 2.5 (if all minor actinides are transmuted and disposed of after 70 years of cooling) and by a factor of 5 to 8 for the same transmutation of all minor actinides, but after 120 years of cooling of the resulting ultimate high level waste. The radiotoxicity of the ultimate waste is reduced by a factor of 10 when only americium being transmuted and by a factor of up to 100 if all minor actinides are transmuted, again compared to an all plutonium multi-recycling scheme which on its own already reduces the radiotoxicity content of the ultimate waste by a factor 10 compared to a LWR once through fuel cycle. However, such advanced all minor actinide management schemes cannot be realized in the short or medium term and demand a significant amount of R&D and, if decided upon and considered overall technologically feasible, would require at least one century of continuous use of nuclear energy to start reducing the minor actinide inventory in geological repositories (while virtually requiring the indefinite continuation of nuclear energy use in increasingly specific or dedicated nuclear reactor systems). The latter would, in particular, apply when the last minor actinide-bearing reactor cores will need to be transmuted, which on itself would be almost a condition to be met in order to truly achieve the radiotoxicity reduction objective. That being said, care has to be taken that the advanced technologies and infrastructure deployed for the purposes of transmutation do not significantly increase overall costs.

It is important to note that, as such, radiological risk from the geological repositories would not be impacted by a reduction of radiotoxicity owing minor actinides transmutation, given the high required performance design and engineering of such repositories. This risk, owing to some long lived fission and activation products that cannot be transmuted, would always remain below the regulatory limits.

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[1] There are many chemical elements and compounds and biological agents that are highly stable in the environment that cause comparable or greater harm to human health than radiation. Many of these chemical and biological substances are more difficult to detect and measure than radiation, which can be detected at minute levels with comparably inexpensive and simple detectors. In fact, the ability to exquisitely detect radiation and radionuclides in minute quantities is associated with very significant public acceptance difficulties. The health effects of low dose radiation are unproven. The fear of low dose radiation is commonly linked psychologically with the origins of nuclear technology in military use and the drawing of a false equivalence between explosive and non-explosive technologies by the general public.

On an international level, nuclear energy cannot be considered without due attention to the inherently dual nature of the potential use of some of the fissile materials and nuclear knowledge required in overall nuclear energy use. The international safeguards regime ensuring a non-proliferation nature of civil nuclear energy use is essential in this respect. While all civil nuclear technologies are safeguardable in principle, as the last decennia have explicitly demonstrated, there is still a concern that the spread of nuclear technology and the advertent diversion of some of the fissile material from the civil nuclear energy installations may not be fully avoided when nuclear energy would become a globally deployed energy source. Some countries have therefore been prohibiting the domestic deployment of used fuel reprocessing and also encouraged other countries to follow this route. At the same time, piling up of the used fuel storages scattered over various reactor sites globally and the 'self-protection' by decay of the used fuel in these storages do not equate univocally to an improved non-proliferation status, especially when considering a worldwide growth in nuclear energy use. With this growth, sustainability of nuclear energy that is essentially driven by cost competitive paths towards reduced natural uranium use per TW·h and the reduced high level waste arising per TW·h may not be achieved without reprocessing and recycling of used fuel over time.

The majority of Generation IV NES concepts rely on one form or another of reprocessing and recycling. During the past decade, multiple national and international studies have concluded that transitioning towards such NESs with enhanced sustainability will take time and needs to be addressed progressively [2.6–2.9]. Taking into account that safety and licensing are essential in nuclear energy, the transition to a closed nuclear fuel cycle should initially involve multi-recycling of plutonium in thermal or fast neutron spectrum reactors, before embarking on a more technologically challenging advanced NESs with some or all of minor actinides added to the nuclear fuel, as such advanced fuels would need performance qualification before ever used. A significant challenge will therefore emerge in the future related to, on the one hand, global deployment of nuclear energy to already address sustainable energy needs and resolve some of the geopolitical tensions a non-sustainable energy future might aggravate, and, on the other hand, the management of increasingly 'closed' nuclear fuel cycles involving fuel operations which are deemed today more proliferation risky than the less sustainable once through fuel cycle on a global level.

When revisiting the potential of nuclear energy to become a sustainable energy source for 'all' globally, it is necessary to recognize that not all of its users will be able to address, or capable of addressing, all sustainability objectives indigenously at once. Some may have to rely on imported 'off the shelf' nuclear technology in absence of a sufficiently developed domestic resource base while others may need low carbon energy rapidly and in massive amounts. In the latter case national nuclear deployment may be impacting the global nuclear energy scene. For example, global natural uranium demand may increase substantively with rapidly growing national nuclear energy deployment, such as planned in China and India in the near future, and this could indirectly hamper the domestic rapid nuclear deployment as well.

The pallet of nuclear energy options to countries embarking on, or moving forward with, nuclear energy as a low carbon energy source is rich and will increasingly demand international and regional cooperation among countries. This on itself is already an important step forward in seeking to ensure a globally sustainable deployment, while securing each country's proper competitive, safe and proliferation resistant use of nuclear energy.

Can such sustainable nuclear energy deployment be undertaken in virtually the same way as done by a few countries during the 20th century, or is increasing collaboration[2] useful or even necessary to provide the path towards worldwide nuclear deployment? Essentially, this is the main question addressed by the Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES) collaborative project, which attempted to investigate synergies of the various kinds within and among NESs, geared towards facilitating the use and deployment of sustainable nuclear energy in a variety of countries across the world. This objective fits well with the path forward set out in President Dwight Eisenhower's Atoms for Peace speech on 8 December 1953[3].

[2] Collaboration is understood here in a broader sense to include collaboration between technology holders and technology users in nuclear fuel cycle, joint ownership of facilities, and multilateral approaches to waste repositories, among other things.

[3] President Eisenhower noted that: "The more important responsibility of this Atomic Energy Agency would be to devise methods whereby this fissionable material would be allocated to serve the peaceful pursuits of mankind. Experts would be mobilized to apply atomic energy to the needs of agriculture, medicine and other peaceful activities. A special purpose would be to provide abundant electrical energy in the power starved areas of the world. Thus, the contributing powers would be dedicating some of their strength to serve the needs, rather than the fears, of mankind." A full transcript of the speech is available at www.iaea.org/about/history/atoms-for-peace-speech

According to Article III of the IAEA Statute:

“B. In carrying out its functions, the Agency shall:

1. Conduct its activities in accordance with the purposes and principles of the United Nations to promote peace and international co-operation...”

Furthermore, according to A. Facilitating access to nuclear power of the IAEA Medium Term Strategy 2012–2017: “The Agency will facilitate and assist international research and development collaboration and partnership for beneficial uses of nuclear energy.”[4]

Synergies within the context of NESs are all actions that a country or a group of countries may undertake to facilitate (i.e. enable, accelerate and optimize) the deployment of an NES aiming at enhanced sustainability of such NESs. Synergies are those actions that make optimal use of a combination of technologies (i.e. synergies of intranuclear options) within the perimeter of a national or regional NES, as well as those that demand more increased cooperation among countries, each with their own NES, but where the cooperation brings benefits in achieving each country’s or collective sustainability objectives of an NES.

The introduction and use of nuclear energy demands a variety of resources ranging from competencies and expertise through education and training, to capacities such as R&D infrastructure and the necessary supply chain capacity which can, to varying degrees, be sourced from the international market. In this, a minimum set of resources is anyhow required in any country embarking or deploying nuclear energy to secure full compliance with safety, safeguards, security and overall operational performance of the nuclear energy as well as nuclear science and technology applications. The SYNERGIES collaborative project focused on synergies among NESs and typically among multiple countries each with its own nuclear energy programme, targeted at achieving long term NES sustainability and had not addressed explicitly the synergies that might exist in the area of nuclear science and technology, R&D infrastructure or education and training, as well as infrastructure issues associated with the deployment of a first nuclear power plant. The latter are addressed specifically in other available IAEA publications (see Refs [2.10, 2.11]). In this publication, the following two kinds of synergies are distinguished:

(a) Synergies in technology: Synergies among technologies with certain complementarity between fuel cycles of different reactors on a purely technical level.
(b) Synergies in collaboration: Synergistic collaboration among countries with different policies with regard to nuclear fuel cycles based on certain arrangements and aimed at bringing the benefits of innovation to all interested users.

The issue of NES sustainability has multiple dimensions [2.12–2.14] with some of the dimensions being directly or indirectly impacted by the nuclear fuel cycle. Indeed, while the local economic competitiveness of nuclear energy is essentially governed by the nuclear power reactor’s economic performance, the longer term sustainability of nuclear energy is essentially governed by the nuclear fuel cycle. The fissile resource and ultimate waste management issues, non-proliferation considerations, the resource and energy independence issue, and even the economic performance through assurance of stable low generation costs of energy are all driven or impacted by the fuel cycle considerations.

It should be noted that certain fuel cycle options are not possible without specific nuclear power plant developments that go hand in hand with the sustainability objectives, and a systems view on sustainable nuclear energy development is therefore essential. With more than two thirds of the life cycle cost of energy generation of nuclear energy defined by the financial settings for nuclear power plants (e.g. overnight capital costs, cost of financing and owners’ cost), these are the local or regional market conditions that would define the economic performance of an NES, and this becomes even more the case when enhanced sustainability oriented NES incorporating more advanced nuclear power plants, typically Generation IV plants, are being considered. Competitive deployment of such systems would require international collaboration at least in R&D (already being accomplished through the Generation IV International Forum programmes) and even in industrial development and deployment.

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[4] See www.iaea.org/sites/default/files/mts2012_2017.pdf

2.2. INPRO CONCEPT OF A SUSTAINABLE NUCLEAR ENERGY SYSTEM

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was established in 2000 to help to ensure that nuclear energy is available to contribute to meeting the energy needs of the 21st century in a sustainable manner. INPRO has introduced the concept of a sustainable NES and developed a methodology for NES assessment [2.12–2.14]. The concept is based on UN definition of sustainable development [2.15]: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", which is then detailed into nuclear specific technical and institutional areas as shown in Fig. 2.1.

The sustainable development received its first major international recognition at the United Nations Conference on the Human Environment, held in Stockholm in 1972. Since then several significant events on the way for sustainable development have taken place. With regard to the latest development, the United Nations Conference on Sustainable Development (Rio+20), in 2012, resulted in an outcome document, The Future We Want [2.16], which contains practical measures for implementing sustainable development. At Rio+20, Member States committed to develop a set of Sustainable Development Goals (SDGs) building on the United Nations Millennium Development Goals and converging with the post-2015 development agenda. They decided to establish the High-level Political Forum on Sustainable Development to replace the Commission on Sustainable Development and to be the main UN platform on sustainable development. It provides political leadership, guidance and recommendations. It follows up and reviews the implementation of sustainable development commitments and, as of 2016, the post-2015 development agenda and the SDGs. It addresses new and emerging challenges, promotes the science–policy interface, and enhances the integration of economic, social and environmental dimensions of sustainable development.

In 2015, a new programme was started to develop the universal, integrated and transformative 2030 Agenda for Sustainable Development. This agenda was launched at a summit in September 2015, and the United Nations General Assembly formally adopted the universal, integrated and transformative 2030 Agenda for Sustainable Development, along with a set of 17 SDGs and 169 associated targets [2.17]. The new goals cover, inter alia, poverty (SDG 1), hunger (SDG 2), good health (SDG 3), clean water (SDG 6), affordable and clean energy (SDG 7), industry and innovation (SDG 9), climate change (SDG 13) and partnership for sustainable development (SDG 17).

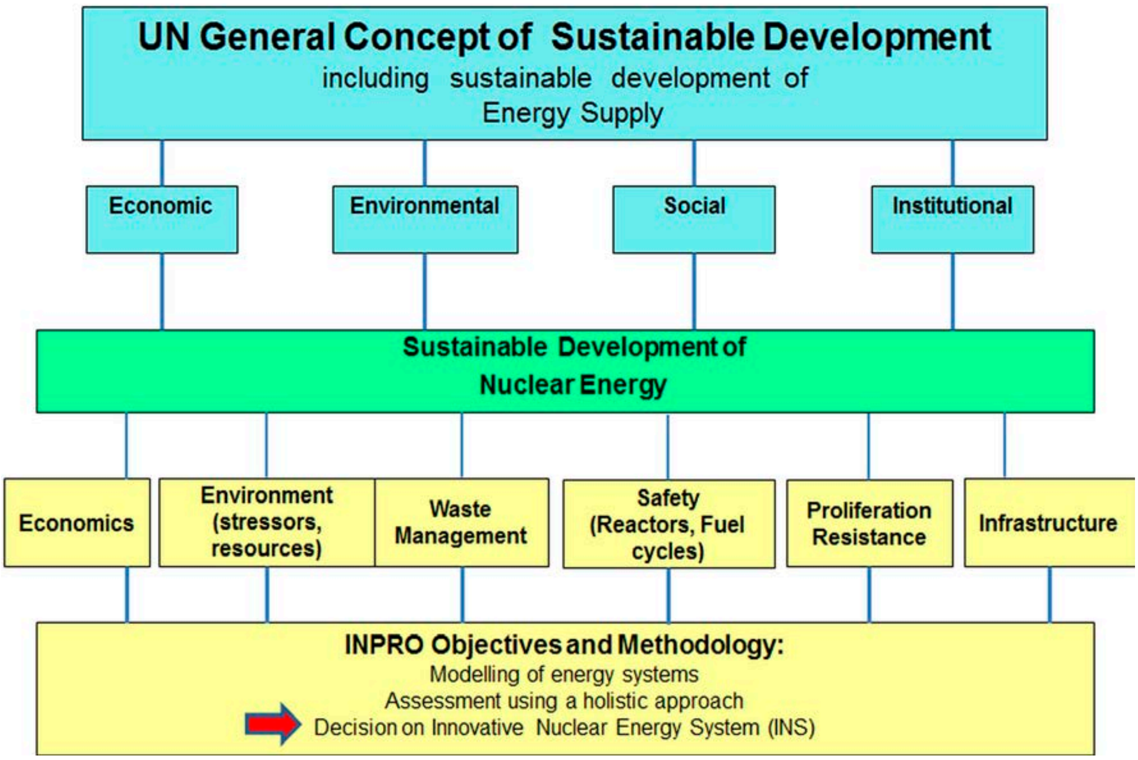


FIG. 2.1. INPRO concept of a sustainable nuclear energy system [2.15].

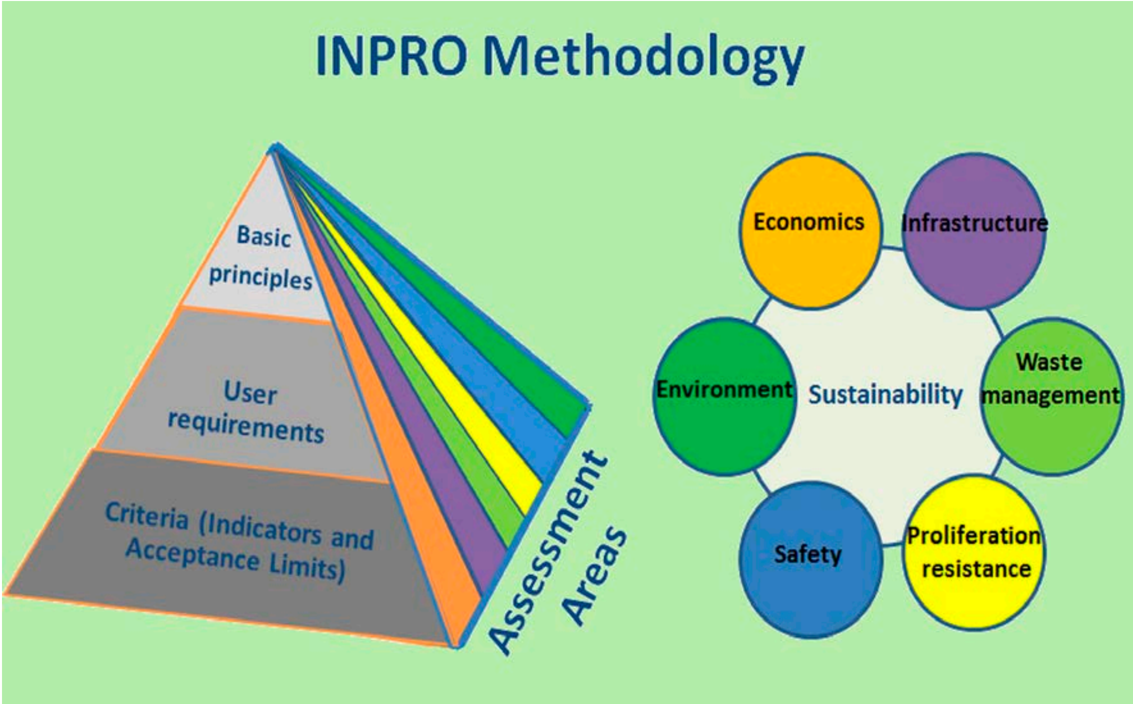


FIG. 2.2. Structure of the INPRO methodology for nuclear energy system assessment.

The INPRO methodology [2.12] remains entirely up to date as the UN/IAEA sustainability assessment for NES, and is neither dated nor superseded. The SDGs are extremely high level, and they simply define targets in large areas. There are two principle SDGs with which NESs directly connect: affordable and clean energy (SDG 7) and climate change (SDG 13). The INPRO technological assessment is comparatively at a low level and has significant detail on a single clean and affordable energy technology area that has a small carbon footprint. SDGs do not go down to this detailed level. Basically, a positive finding on an NES assessment could support partial positive findings on those two SDGs, which aim to "Ensure access to affordable, reliable, sustainable and modern energy for all" and to "Take urgent action to combat climate change and its impacts" [2.17].

The INPRO methodology has a hierarchical structure, as shown in Fig. 2.2. At the top are the basic principles, which are sustainability objectives in particular technical or institutional areas. User requirements located one level down show what needs to be achieved to meet the sustainability objectives (basic principles). Each basic principle has one or more user requirements associated with it. Finally, at the bottom is INPRO metrics (the criteria which consist of indicators and acceptance limits), which helps the assessor to verify whether user requirements are fulfilled for the NES under assessment. Each user requirement has one or more criteria. In the current version of the methodology, there are 14 basic principles, 52 user requirements and 125 criteria in the seven INPRO subject areas (Economics, Safety, Waste Management, Proliferation Resistance, Physical Protection, Environment and Infrastructure), as shown in Fig. 2.2. Meeting all of the criteria means that NES is sustainable and has a high potential to contribute to growing energy needs in the 21st century [2.12–2.14].

2.3. SUSTAINABILITY ASPECTS OF NUCLEAR ENERGY DEVELOPMENT SCENARIOS

INPRO Task 1: Global Scenarios develops regional and global nuclear energy scenarios that contribute to developing a global vision on how sustainability of nuclear energy could be enhanced within the present century [2.18]. By developing those scenarios, INPRO helps both newcomers and existing nuclear countries to understand the key issues in a transition to future sustainable NESs, the role that innovations and collaboration among technology holders and technology users could play in such a transition. As reported in Ref. [2.18]:

> "The economic studies carried out by INPRO have shown that investments in Research, Design & Demonstration (RD&D) for innovative technologies, such as fast reactors and a closed nuclear fuel cycles, are huge and provide reasonable pay-back times only in the case of a foreseen large scale deployment of such technologies. Not all of the countries interested in nuclear energy could and would afford such investments. Then, benefits associated with innovative technologies can be amplified, and may also be brought to many interested users through mutually beneficial cooperation among countries in fuel cycle back end."

To take this into account, the INPRO collaborative project on Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS), conducted in 2008–2011 [2.6], has introduced a heterogeneous world model to reflect upon different policies of different countries with respect to the nuclear fuel cycle and, specifically, its back end. This model enables analysing options for cooperation among countries in a nuclear fuel cycle (see Appendix III) [2.18].

The GAINS heterogeneous world model, which is part of the Analytical Framework for Analysis and Assessment of Transition Scenarios to Sustainable Nuclear Energy Systems [2.19], has developed its own metrics to assess transition scenarios to sustainable NESs (see Table 2.1). Key indicators typically have a distinctive capability for capturing the essence of a particular area, and those areas are identified by a bold '**X**' [2.6].

The GAINS metrics builds upon the INPRO methodology for NES assessment but in most cases does not duplicate it. It is narrower and focuses on the areas that are important for scenario analysis (i.e. can be assessed through material flow analysis and associated economic analysis). The major areas are resource availability and production of waste, the associate power capacity curves for nuclear reactors involved, radioactivity and radiotoxicity of waste, but also demand in fuel cycle services and costs and the required investments. Such important areas as safety and physical protection are not covered under the GAINS metrics but are assumed to be thoroughly evaluated under other assessments based on the INPRO methodology [2.20].

It is namely the GAINS notion of sustainability and the GAINS metrics that was used and elaborated (see Appendix I) in the studies carried out within the SYNERGIES project. The objective was to examine the scenarios moving both technology holders and technology users towards sustainable nuclear energy solutions in terms of sufficient resources and minimum waste, timely achievement of targeted capacity evolution curves, minimization of long lived radiotoxicity, amplifying the benefits of innovative technologies that are costly to develop to bring them to a wide range of users in an affordable way through mutually beneficial cooperation with technology holder countries in fuel cycle back end. Drivers and impediments for such collaborative scenarios were then examined, including, but not limited to, economic benefits to both, technology holders and technology users.

2.4. SUSTAINABILITY ENHANCEMENT ISSUES AND POSSIBLE SOLUTIONS

In terms of the scope of the SYNERGIES project (focused on the material flow and economic analyses), the major long term sustainability enhancement issues addressed are as follows:

(a) Progressive accumulation of spent nuclear fuel that creates a burden for future generations;
(b) Non-effective use of natural fissile resources that in the future might create problems related to fissile resource non-availability;
(c) Presence of direct use materials (plutonium) in spent nuclear fuel, first in irradiated form, and, in several hundreds of years, already in a form that might be rated as unirradiated and that might create long lasting (hundreds of thousands of years) proliferation resistance and security concerns in the case of direct disposal of spent nuclear fuel in non-nuclear-weapon States;
(d) Huge investments required to develop and deploy innovative technologies for nuclear power, making such innovative options unaffordable for many current and potential users of nuclear technology;
(e) Risks related to global spread of sensitive technologies of uranium enrichment and spent fuel reprocessing, addressing the consequences of which would be a huge burden for future generations.

The above mentioned issues could be effectively addressed with innovative technologies, such as fast reactors and a closed nuclear fuel cycle, but also several others. However, as the experiences of Member States show, development and implementation of new technologies requires huge financial resources, and the resulting

TABLE 2.1. GAINS KEY INDICATORS AND EVALUATION PARAMETERS [2.6]

No.	Key indicators and evaluation parameters		INPRO assessment areas					
	Colour coding indicative of relative uncertainty level in estimating specific quantitative values for future NESs (can vary based on a particular scenario)	Low Medium low Medium high High	Resource Sustainability	Waste Management and Environment Stressors	Safety	Proliferation Resistance and Physical Protection	Economics	Infrastructure
Power production								
KI-1	Nuclear power production capacity by reactor type							X
EP-1.1	(a) Commissioning and (b) decommissioning rates			X				X
Nuclear material resources								
KI-2	Average net energy produced per unit mass of natural uranium		X	X				
EP-2.1	Cumulative demand of natural nuclear material, i.e. (a) natural uranium and (b) thorium		X	X				
KI-3	Direct use material inventories per unit energy generated (cumulative absolute quantities can be shown as EP-3.1)		X			X		X
Discharged fuel								
KI-4	Discharged fuel inventories per unit energy generated (cumulative absolute quantities can be shown as EP-3.1)			X				X
Radioactive waste and minor actinides								
KI-5	Radioactive waste inventories per unit energy generated (cumulative absolute quantities can be shown as EP-5.3)			X				X
EP-5.1	(a) Radiotoxicity and (b) decay heat of waste, including discharged fuel destined for disposal			X				X
EP-5.2	Minor actinide inventories per unit energy generated			X				X
Fuel cycle services								
KI-6	(a) Uranium enrichment and (b) fuel reprocessing capacity, both normalized per unit of nuclear power production capacity					X		X
KI-7	Annual quantities of fuel and waste material transported between groups			X		X		X
EP-7.1	Category of nuclear material transported between groups					X		
Safe system								
KI-8	Annual collective risk per unit energy generation				X			

TABLE 2.1. GAINS KEY INDICATORS AND EVALUATION PARAMETERS [2.6] (cont.)

No.	Key indicators and evaluation parameters		INPRO assessment areas					
	Colour coding indicative of relative uncertainty level in estimating specific quantitative values for future NESs (can vary based on a particular scenario)	Low / Medium low / Medium high / High	Resource Sustainability	Waste Management and Environment Stressors	Safety	Proliferation Resistance and Physical Protection	Economics	Infrastructure
Cost and investment								
KI-9	Levelized unit of electricity cost						X	
EP-9.1	Overnight cost for *N*th-of-a-kind reactor unit: (a) total and (b) specific (per unit capacity)						X	
KI-10	Estimated R&D investment in *N*th-of-a-kind deployment						**X**	X
EP-10.1	Additional function or benefits						X	

economic benefits are visible only for scenarios with large scale deployment of such technologies [2.6], also contributing to the accelerated economies of scale or numbers. Moreover, some of such technologies, such as enrichment and spent fuel reprocessing where direct use/weapons usable materials are present in bulk form, are proliferation sensitive. With these limitations in place, it is collaboration among countries in nuclear fuel cycle that could bring the benefits of enhanced sustainability originally available only to technology holder countries to a broader variety of users, including those who will not be able or willing to deploy innovative technologies [2.6].

For the purpose of scenario studies focused on options of cooperation among countries in nuclear fuel cycle, and taking into account the overall known potential of nuclear technology (both, proven and yet to be proven) and nuclear trade, INPRO Task 1: Global Scenarios has developed a concept of ‘Options for enhanced nuclear energy sustainability’, included as Appendix V to this publication. This concept addresses both, technology related and collaboration related options.

The technology related options are structured along generic fuel cycle options, with generic reactor options linked to fuel cycle options. The reason for this is that the generic reactor technologies may be common for several generic fuel cycle options, while the generic fuel cycle options are limited in number and well known. The details on nuclear reactors associated with the defined fuel cycle options are provided in Appendix V.

With respect to fuel cycle technology, the following options have been defined:

— Option A. Once through nuclear fuel cycle;
— Option B. Recycle of spent fuel with only physical processing;
— Option C. Limited recycling of spent fuel;
— Option D. Complete recycle of spent fuel;
— Option E. Minor actinide or minor actinides and fission products transmutation;
— Option F. Final geological disposal of all wastes.

Option F (final geological disposal of spent nuclear fuel/high level radioactive waste) applies to all Options A–E above. In this context, each generic fuel cycle option can be amended by adding Option F (e.g. AF, BF, CF and so forth) and only with such amendment could they be considered for sustainability.

Sustainability Option A is fundamental to any sustainable NES. Options B–E can progressively improve resource sustainability of an NES while also substantially reducing the long term waste burden. This in turn can facilitate the achievement of Option F. However, care needs to be taken that the advanced technologies and infrastructure deployed do not significantly increase costs. Competitive economics versus other energy options is, and would remain, an important driver for nuclear energy development, along with national and international considerations such as diversification of resources or environmental objectives such as greenhouse gas reduction. It could also be noted that moving from Option AF to Option EF may be a dynamic process.

In the above mentioned classification, Option A represents technologies commercially available today (thermal reactors, and wet and dry storages of spent nuclear fuel). Some Option C technologies are also commercially available today in a limited number of technology holder countries. For the other options research, development and demonstration is in progress in a number of countries, including under international collaborations such as the Generation IV International Forum and the European Sustainable Nuclear Industrial Initiative. With regard to collaboration among countries in peaceful uses of nuclear energy, it was noted that options for such collaboration are governed by bilateral and multiple bilateral agreements and multilateral agreements.

If considered superficially, the agreements governing international trade and cooperation on nuclear power and fuel cycle may seem to hamper competitive trade as found in less regulated markets. However, peaceful nuclear energy development and trade implies transfer of considerable and unique responsibilities and liabilities. The sophisticated nuclear trade regime helps to manage these specific and unique risks associated with nuclear energy development.

In Appendix V, it is also noted that, although rare, some examples of multilateral agreements (e.g. Treaty establishing the European Atomic Energy Community), as well as the emerging multiplicity of suppliers and bilateral agreements among certain countries (nuclear power plants, fuel supplies and services) indicate that benefits of competitive trade can be achieved in the future for a variety of supplies in nuclear power and the nuclear fuel cycle, within the established governance models of international nuclear trade and cooperation [2.21]. International cooperation is also viewed crucial in developing the next generation of nuclear reactors.

It should be noted that the concluded SYNERGIES collaborative project had no objective to examine particular forms of collaboration among countries in nuclear fuel cycle and legal and institutional issues arising thereof, which could become the subject of a dedicated future study. The project addressed more generic issues related to synergies among nuclear technologies and options to ‘amplify’ their positive effects through collaboration among countries.

2.5. RESULTS OF PREVIOUS SCENARIO STUDIES

The collaborative project GAINS [2.6, 2.18] used heterogeneous global model to identify how the benefits of innovative technologies could be amplified and delivered to a variety of users, including those who do not plan to deploy the innovative systems, through collaboration among countries in nuclear fuel cycle back end. The innovations such as fast reactors and a closed nuclear fuel cycle were considered in that study.

(a) (b) (c)

FIG. 2.3. World models for fuel cycle analysis used in GAINS, (a) homogeneous, (b) heterogeneous non-synergistic, (c) heterogeneous synergistic [2.6].

In GAINS, three groups of non-geographical, non-personified countries (NGs) were defined as follows (see Fig. 2.3) [2.6, 2.18]: NG1 recycles spent nuclear fuel and pursues a fast reactor programme; NG2 directly disposes of spent nuclear fuel or sends it for reprocessing to NG1; and NG3 sends spent nuclear fuel to NG1 or NG2. In this, NG1 is representative of some technology holder countries. NG2 represents experienced users, while NG3 represents newcomer countries.

With regard to fuel cycle back end, the countries denoted by NG1, 2, 3 could go on independently, for example with long term controlled storage of spent nuclear fuel pending competitive proven technology of its management/disposal (heterogeneous non-synergistic case shown in Fig. 2.3(b)). Or, alternatively, the countries could cooperate. A form of cooperation that potentially may offer sustainability benefits to all NGs, to which GAINS referred as 'synergistic' (see Fig. 2.3(c)), is related to NG2 and NG2 sending their spent fuel to NG1, for reprocessing and use as a startup load in NG1's fast reactor programmes.

With regard to such synergistic collaboration, GAINS has concluded the following [2.20]:

(1) Although only a few countries would master innovative technologies of fast reactors and closed nuclear fuel cycle within this century, all others could benefit from this if they follow a synergistic approach (i.e. send their spent nuclear fuel for reprocessing and recycle in fast reactor programmes implemented by 'fast reactor countries'). In this, progressive accumulation of spent nuclear fuel on a global or regional scale could be mitigated or even reversed to limit the inventory of such fuel to minor actinides and fission products or only fission products, if minor actinides are further incinerated in dedicated transmutation systems.

(2) The above mentioned synergistic approach within a heterogeneous world offers potential benefits associated with reducing both, inventories of direct use material (plutonium) and the number of sites using sensitive technology of fuel reprocessing. GAINS calculations have shown under a synergistic approach global plutonium inventory could be reduced down to a minimum stock needed for NES operation.

(3) A synergistic approach could also secure natural uranium saving of up to 40%, compared to heterogeneous non-synergistic case.

(4) Countries that do not implement fast reactor programmes could benefit from the synergistic approach, as it offers reduced requirements to long term spent fuel storage and ultimate disposal of waste. Even if fission products are returned, their volume will be substantially smaller compared to spent fuel before reprocessing and, additionally, proliferation concerns will not exist for storages or final disposals of such waste.

(5) Within the considered synergistic approach, all countries could benefit from lower cost of fuel cycle services owing to economies of scale and economies of accelerated learning. As natural uranium resource is also being saved through synergistic cooperation, all countries could also benefit from longer lasting lower costs of natural uranium.

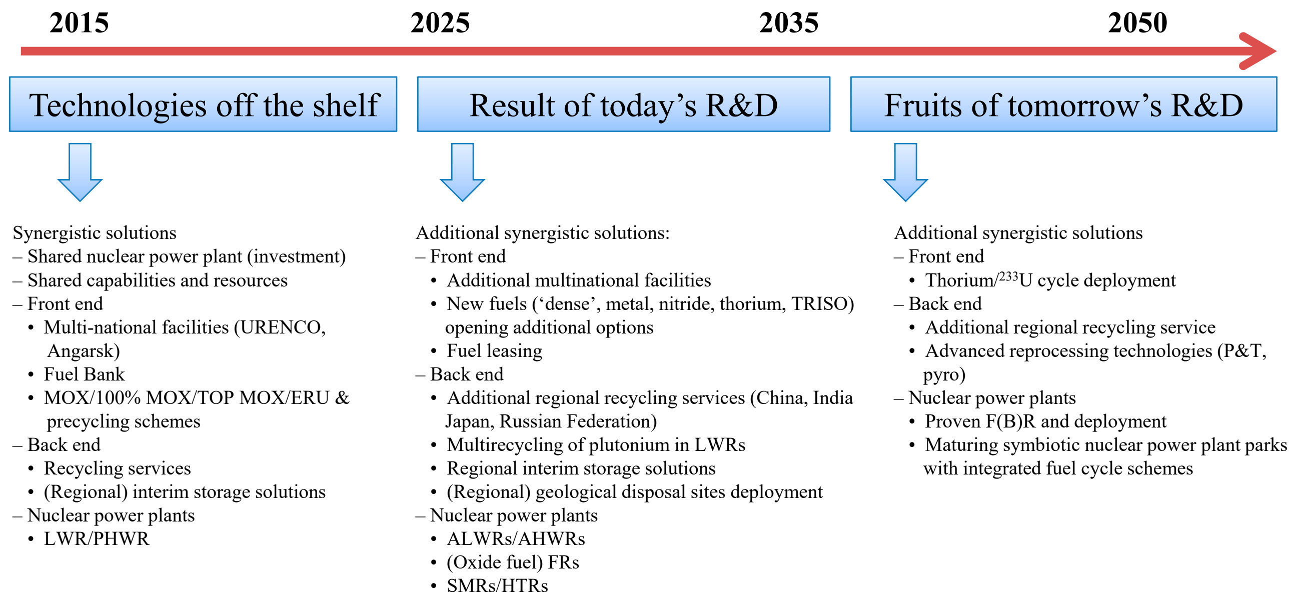
(6) The reprocessing capacity requirements will increase for NG1 countries in the case of spent fuel shipment from non-NG1; however, in this case NG1 countries would acquire larger fissile resource to go on with expansion of their closed fuel cycle and fast reactor programmes, benefiting from smaller research, development and demonstration risks and shorter pay back time on investments.

The GAINS collaborative project has focused on fuel cycle back end synergies only between two technologies, which are uranium LWRs in a once through fuel cycle and fast reactors with the initial uranium–plutonium load produced via reprocessing of LWR spent fuel. The SYNERGIES collaborative project, presented in this publication, took a follow-up on this to consider synergies among broader variety of technologies[5] and synergistic collaborations among users of such technologies and to identify drivers and impediments for such collaborations.

2.6. SYNERGIES STORYLINES

Reflecting on the results of the previous studies [2.6, 2.26–2.28] and taking into account consolidated opinion of the SYNERGIES participants, the storyline shown in Fig. 2.4 was selected as reflecting the scope of the case studies performed within the SYNERGIES collaborative project. This storyline loosely reflects the outcome of

[5] See Refs [2.6, 2.22–2.25] to learn more about the impact of the various advanced nuclear reactors on nuclear energy scenario sustainability indicators, as well as about the status of technology and design development for innovative and advanced reactors.



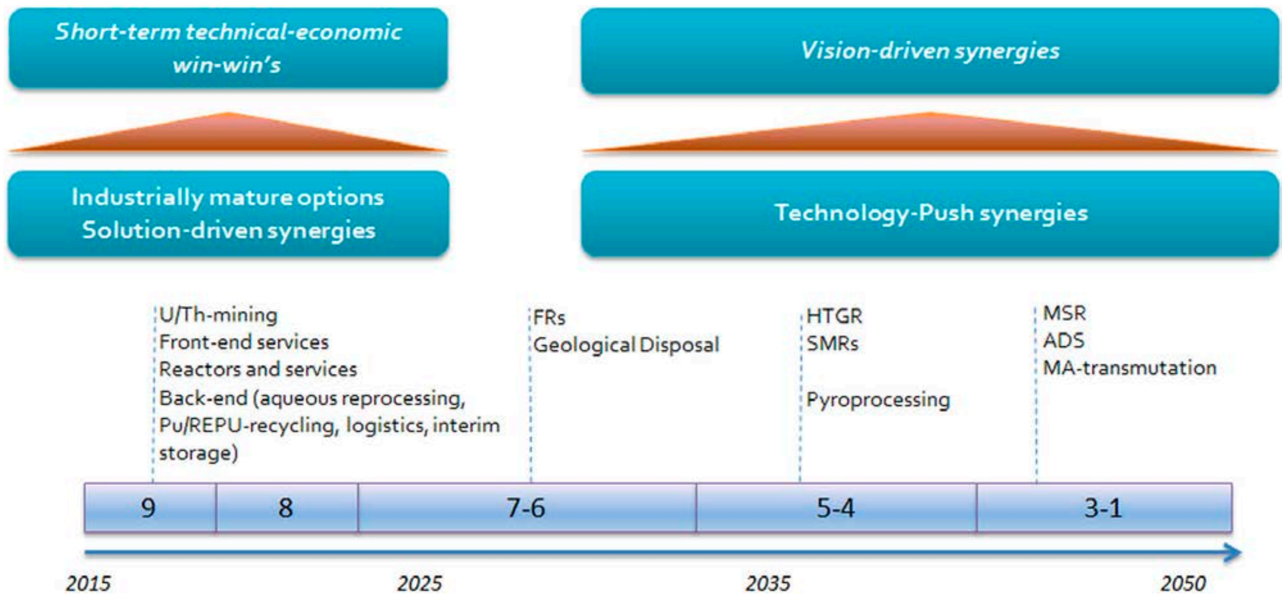
Note: AHWR — advanced heavy water reactor; ALWR — advanced light water reactor; ERU — enriched uranium; F(B)R — fast (breeder) reactor; HTR — high temperature reactor; LWR — light water reactor; MOX — mixed oxide; P&T — partitioning and transmutation; PHWR — pressurized heavy water reactor; SMR — small modular reactor; TRISO — tristructural isotropic fuel; TOP-MOX is a MOX fuel supply contract under which the supplied MOX fuel contains more plutonium than was present in the spent fuel through reprocessing of which MOX fuel was produced.

FIG. 2.4. SYNERGIES storyline.

various nuclear technology roadmap studies from the past few years [2.26]. Figure 2.4 gives a graphic summary of the outcome of various nuclear technology roadmap studies from the past few years [2.22], and it provides a time framed illustration of anticipated technological and collaborative developments to be observed worldwide within the present century. The three time frames[6] (i.e. before 2025, 2025–2035 and post-2035) are distinguished as the following:

(a) The first time frame addresses essentially the short term issues and challenges that the various Member States may face today and in the near future. Addressing these in a 'win-win' mode, while providing prospects to the medium and longer term sustainable development, is important, if not crucial, for the interested Member States. The options considered here are those based on what is already an industrial practice at present or what represents the results of the ongoing R&D and that can be applied in a very short term.
(b) The second time frame would be enabled mainly by the ongoing R&D and the R&D that can be industrialized or made operational within the coming roughly two decades. The various R&D avenues available today, in particular those related to the fuel cycle and Generation IV NESs, may see varying degrees towards demonstration and early industrialization in some countries, and may also be of high importance for interested Member States especially as comes to bi/multilateral or regional, or even global collaboration. In many cases, these may be centred around regional platforms seeking further optimization of the present and near future fuel cycle services and infrastructure.
(c) Part of the ongoing R&D may find their industrial deployment in the post-2035 time period. Geological disposal sites are anticipated to be under development or even operational by that time, early after 2035 some of the present day fuel cycle infrastructure might be replaced in the context of sustainable NESs, such as the Generation IV systems; in this, multilateral or regional deployment schemes are potentially crucial for realization. The third time frame of Fig. 2.4 is essentially addressing options where synergies can be an accelerating factor towards realization, while also providing the vision required to make such synergies happen.

6 The time frame is hereby related to the level of technical economic readiness of the system components for synergies (when such synergies could be considered).



Note: ADS — accelerator driven system; FR — fast reactor; HTGR — high temperature gas cooled reactor; MA — minor actinide; MSR — molten salt reactor; SMR — small modular reactor; REPU — reprocessed uranium.

FIG. 2.5. Nature of synergies within the SYNERGIES storyline (for illustration only, the lower bar shows the degree of technological readiness in conventional units corresponding to Ref. [2.29]).

Figure 2.5 provides an illustration of the nature of the explored synergies towards NESs with enhanced sustainability as suggested by the SYNERGIES storyline of Fig. 2.4. Within the first time frame shown in Fig. 2.5 synergies are mostly driven by 'win-win' situations defined by the present day technical–economic solutions, while within the third and, to a certain degree, also within the second time frame a more 'vision driven' approach towards NESs of enhanced sustainability will be required, to be boosted by technology push actions from innovative technology developers.

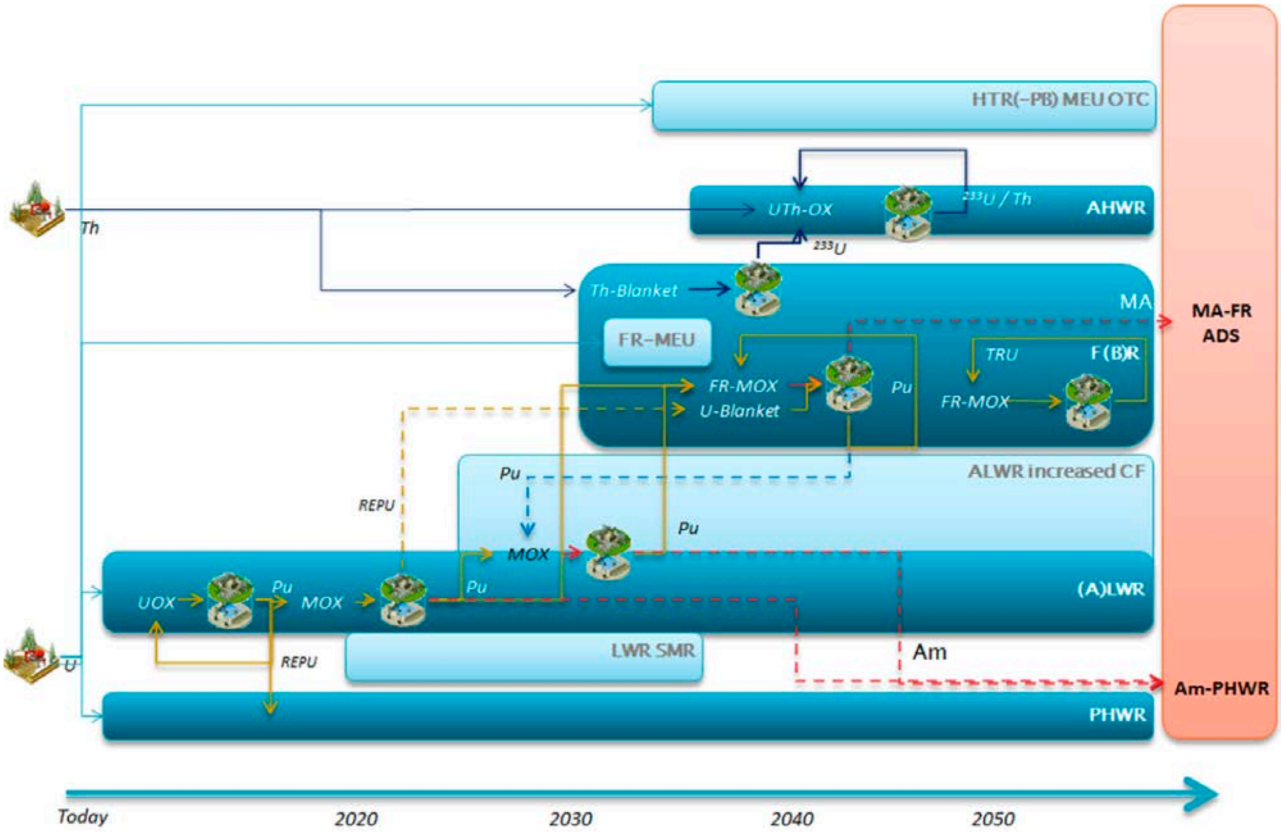
The deployment of NESs in different countries worldwide may take place independently, notwithstanding the fact that most of the technologies to be deployed will be resourced from a limited number of vendors. Taking into account the high costs of nuclear technology development, it is highly likely that only a few countries will be able to afford a domestic indigenous NES development and deployment [2.6]. Therefore, for the future NESs to be globally sustainable, a combination of the various, above mentioned, synergistic collaborations may be needed, depending on the pace of nuclear capacity growth. Such collaborations are likely to be case specific at lower pace of nuclear deployment, but may become more universal at a globally higher pace of nuclear energy deployment.

In line with the evolving technical–economic conditions for NES sustainability, especially those related to economic competitiveness in local markets, an increasing number of synergies between local markets (essentially, the countries to which these markets belong) could be considered and developed aiding each of them to advance in the use of nuclear energy as part of their sustainable energy mix. The present view on sustainability oriented synergies among the technologies and possible synergistic collaborations is represented by the 28 case studies presented in Section 3 of this publication.

2.7. SYNERGIES SCENARIO FAMILIES

2.7.1. Overall scope of synergies' consideration

Figure 2.6 shows, in a schematic way, the NES options and the corresponding scenarios analysed in this publication as representative for synergistic approaches to deployment of NESs of enhanced sustainability. These scenarios are detailed in Section 3, where they are analysed with dynamic NES codes and economic assessment tools as part of the illustrative picture indicating synergistic sustainability potential of certain strategies.



Note: ADS — accelerator driven system; AHWR — advanced heavy water reactor; (A)LWR — (advanced) light water reactor; CF — conversion factor; F(B)R — fast (breeder) reactor; HTR — high temperature reactor; MA — minor actinide; MOX — mixed oxide; PHWR — pressurized heavy water reactor; REPU — reprocessed uranium; SMR — small modular reactor; TRU — transuranic; UOX — uranium oxide. For reasons of simplicity, waste streams are not shown in this figure. The issues of final disposal and wastes are discussed in detail in Appendix V and in Section 2.4.

FIG. 2.6. Overall view of the considered synergies among the technologies.

While all synergies considered in this publication are of an intranuclear nature, they could be systematized in two groups. The first one includes synergies that are of an essentially ‘technical’ nature that can be considered, at least in principle, within one large enough national NES. The second one comprises the cases where a combination of NESs across countries may bring benefits that each of the countries alone would not be able to achieve. This systematization is used as one of the attributes for the case studies presented in Table 3.1, in Section 3.

It should be noted that even for the essentially ‘technical’ synergies that can, in principle, be achieved within the boundaries of a single large enough national nuclear programme, cooperation with other countries would in most cases be helpful to enable, accelerate or optimize the ‘technical’ synergies, as well as to bring into the picture international and other national institutional requirements.

Figure 2.6 illustrates possible ‘technical’ synergies between reactors of different types and the associated fuel cycles. Options to amplify sustainability related benefits from such synergies through collaboration among countries in nuclear fuel cycle are then analysed in the 19 case studies presented in Section 3 (see Table 3.1). Specifically, collaborative approach appears to be helpful when the ‘optimal’ ratio of reactors of different types cannot be obtained in smaller NESs. In this case, international collaboration is required to make the mass flows in the synergistic NES work ‘optimally’ (i.e. geared towards delivering on sustainability objectives).

In the following Sections 2.7.2–2.7.5, the overall picture shown in Fig. 2.6 is split into simpler graphic presentations representing each of the selected SYNERGIES scenario families (see Section 1.3), with explanations provided for each family. Table 2.2 illustrates the relationship between the sustainability options defined in Section 2.4 (see also Appendix V) and the scenarios in the scenario families considered in this publication (see Section 3).

TABLE 2.2. SYNERGIES SCENARIO FAMILIES VERSUS OPTIONS FOR ENHANCED NUCLEAR ENERGY SUSTAINABILITY

Scenario family Option for enhanced nuclear energy sustainability	Business as usual scenarios consisting of once through fuel cycle and mono-recycling of U/Pu in thermal spectrum reactors (Scenario family A)	Scenarios with the introduction of a number of fast reactors to support multi-recycling of Pu in LWRs and fast reactors (Scenario family B)	Fast reactor centred scenarios enveloping scenarios with reprocessing of thermal reactor fuel to enable noticeable growth rate of fast reactor capacity (Scenario family C)	Scenarios of transition to Th/^{233}U fuel cycle and scenarios with alternative U/Pu/Th fuel cycles (Scenario family D)
Option A. Once through nuclear fuel cycle	+	–	–	+
Option B. Recycle of spent fuel with only physical processing	+	–	–	–
Option C. Limited recycling of spent fuel	+	–	–	–
Option D. Complete recycle of spent fuel	–	+	+	+
Option E. Minor actinide or minor actinides and fission products transmutation	–	–	+ Dedicated systems (ADS, MSR) are also being considered for this purpose	+ Transfer to ^{233}U–Th fuel cycle reduces the generation of MA Dedicated systems (ADS, MSR) are also being considered for this purpose
Option F. Final geological disposal of all wastes	+	+	+	+

Note: ADS — accelerator driven system; MA — minor actinide; MSR — molten salt reactor.

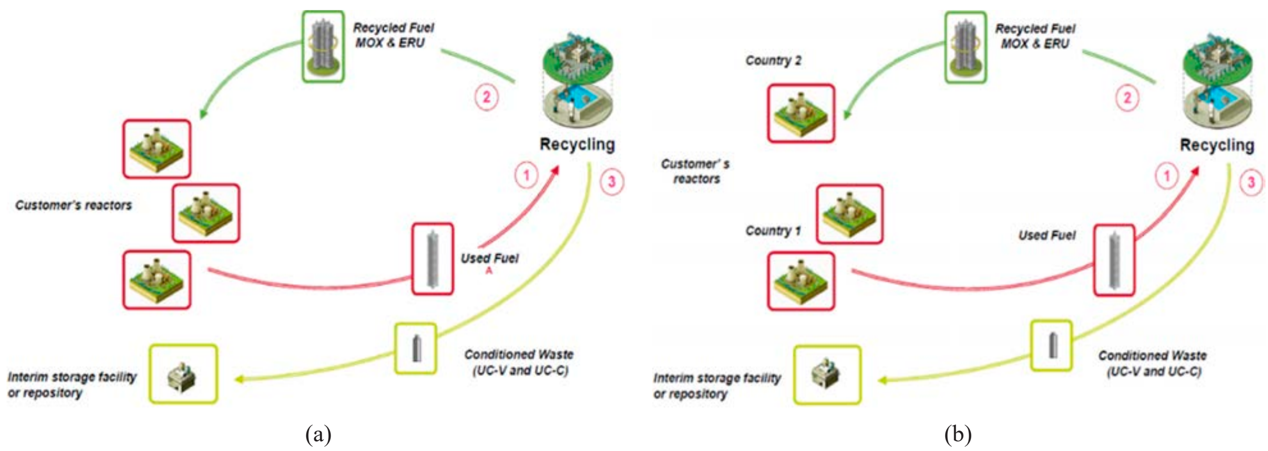
2.7.2. Business as usual scenarios consisting of once through fuel cycle and mono-recycling of U/Pu in thermal spectrum reactors (Scenario family A)

Present day NESs are mostly based on the use of natural uranium in pressurized heavy water reactors (PHWRs) and enriched natural uranium in LWRs, and most of the NESs today use the enriched natural uranium in a once through fuel cycle. Given the potential pressure on the natural uranium market, especially in view of the growing global nuclear energy demand, and specifically due to the non-sustainable growth of spent (used) fuel inventories, some countries and particularly those with rapidly growing nuclear energy parks have embarked on a recycling of the plutonium and uranium from LWR used uranium dioxide fuel after its first pass through LWRs. The use of MOX LWR fuel is the prime example of mono-recycling of uranium and plutonium in thermal spectrum reactors benefiting from already more than 20 years of industrial experience [2.30, 2.31]. The separated reprocessed uranium can be recycled in LWRs as well as in PHWRs [2.32] (see Fig. 2.7).

This first step towards enhanced NES sustainability (reduction of used fuel inventories, expansion of available fissile resource) already suggests a variety of options for synergistic collaboration among countries, such as sharing of nuclear fuel cycle facilities (e.g. reprocessing in regional fuel cycle centres) potentially allowing more countries to access the mono-plutonium and mono-uranium recycling strategy. For a number of countries (e.g. in Europe), this already presents a viable synergistic option alleviating the growing used fuel inventory in fuel cycle back end and, in some cases, also alleviating the need to deploy a non-economical national geological disposal facility (see Figs 2.8 and 2.9). The case studies illustrating such scenarios are presented in Section 3.2.

Note: (A)LWR — (advanced) light water reactor; MOX — mixed oxide; PHWR — pressurized heavy water reactor; REPU — reprocessed uranium; UOX — uranium oxide.

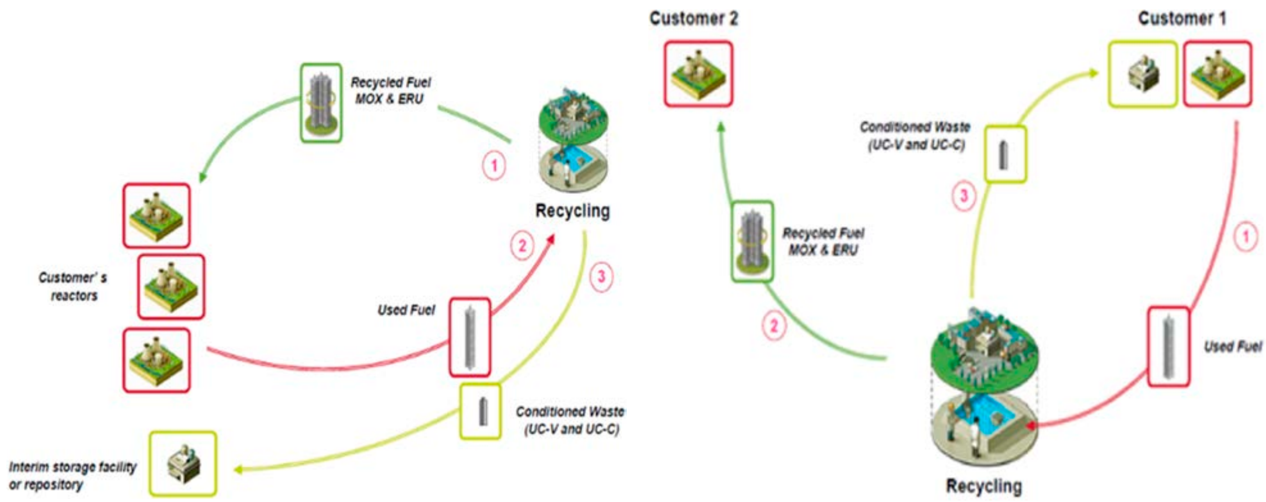
FIG. 2.7. Business as usual scenarios consisting of once through fuel cycle and mono-recycling of U/Pu in thermal spectrum reactors (Scenario family A).



Note: ERU — enriched uranium; MOX — mixed oxide; UC-C — universal canister for compacted waste; UC-V — universal canister for vitrified waste.

FIG. 2.8. Classical scheme (a) of U/Pu recycling where a country uses domestic and (b) regional fuel cycle services shared among multiple countries or the utilities active in multiple countries.

Various synergies can exist (or already exist) in this first phase of NES development towards enhanced sustainability, ranging from co-investment in front end fuel cycle services, such as mining and enrichment capacity reservation (e.g. URENCO, George Besse II), as well as in the back end and waste management activities, such as regional interim storages, regional geological disposals [2.21] and, potentially, regional fuel cycle centres [2.9, 2.33].



(a) (b)

Note: ERU — enriched uranium; MOX — mixed oxide; UC-C — universal canister for compacted waste; UC-V — universal canister for vitrified waste.

FIG. 2.9. Pre-cycling (a) and TOP-MOX scheme (b) of plutonium recycling where a country benefits from a regional fuel cycle centre in proactively reducing its U_{nat} requirements and used fuel storage requirements by earlier introduction of plutonium recycling.

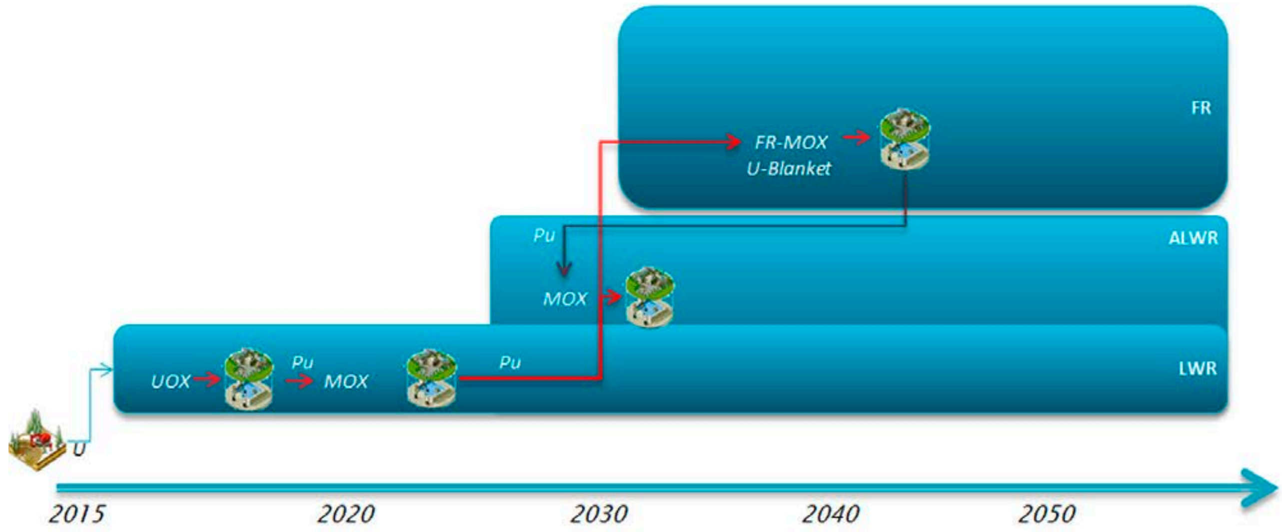
More recent approaches consist of further improving the recycling of materials, specifically plutonium, in a multicountry context where one country (1), still in anticipation of a transition towards a closed fuel cycle or not considering it all, is already receiving LWR MOX fuel based on the plutonium produced from the reprocessing of used nuclear fuel originating from another country (2) (see pre-cycling option in Fig. 2.9). In this approach, country 1 would benefit from earlier savings in front end fuel cycle services, while country 2 would be alleviated from piling up LWR UOX used fuel inventories. Such schemes can allow significant savings for both countries and are being considered today by some countries.

Once the first uranium or plutonium recycle is undertaken, there would be a slowly growing used MOX fuel inventory where LWRs may allow for a second recycle of the plutonium from such MOX (subject to specific core management or plutonium management, dependent on the various used UOX inventories). In addition to this, newer generation LWRs provide the option of a 100% MOX core, also allowing to recycle such second generation plutonium into MOX, although resulting in a less significant natural uranium per TW·h reduction as compared to the first plutonium recycle.

Due to neutron physics related reasons, the recycling of plutonium in thermal reactor systems is limited, and there would inevitably come the time when an additional inflow of ‘better quality’ plutonium will be needed to allow for continued plutonium recycling in LWRs. Multiple variants could be considered for this purpose, for example mixing of the various plutonium flows coming from the various UOX used fuel compositions. Although also limited in time, this could be realized by mixing the used fuel coming from different countries. Again, those countries that do not consider embarking on a used fuel recycle, but are being faced with growing LWR UOX used fuel inventories, may consider providing their used fuel for reprocessing, whereby the separated plutonium could be rendered into value by upgrading the isotopic plutonium composition in countries that have already embarked on using the (partially) closed nuclear fuel cycle.

2.7.3. Scenarios with the introduction of a number of fast reactors to support multi-recycling of Pu in LWRs and fast reactors (Scenario family B)

To ensure long term sustainable plutonium multi-recycling in thermal spectrum reactors, the plutonium composition corresponding to used fuel from LWRs could be upgraded by introduction of the plutonium coming from fast reactors (i.e. the one that is essentially bred in a fast reactor core or blankets, see Fig. 2.10). This option could be realized with both, breeder and burner fast reactors, as the plutonium from a fast reactor core or blanket could be just replaced by the plutonium coming from LWR used fuel.



Note: ALWR — advanced light water reactor; FR — fast reactor; LWR — light water reactor; MOX — mixed oxide; UOX — uranium oxide.

FIG. 2.10. Scenarios with the introduction of a number of fast reactors to support multi-recycling of Pu in LWRs and fast reactors (Scenario family B).

In rapidly growing NESs, such as those planned in China and India, the deployment of fast reactors is seen as a major priority, while in other countries with more modest planned nuclear expansion or even stagnation the deployment potential of fast reactors is limited. But in any case, fast reactors are likely to be only few at early stages of their deployment, just because they will need time to acquire proofs of reliable operation and economic competitiveness before being deployed at a larger scale.

Scenarios with the initial introduction of a limited number of fast reactors offer large flexibility with respect to their further evolution and better match the developments observed in technology holder countries worldwide. Indeed, such scenarios appear to bear minimum risks related to potential delays in large scale deployment of fast reactors in technology holder countries and, at the same time, may offer tangible benefits to both, technology holders and technology users, related to minimization of high level radioactive waste and expansion of the available fissile resource, achieved through collaboration among countries in fuel cycle back end. With regard to their further evolution, such scenarios allow to move to large scale fast reactor/closed fuel cycle deployment programmes in technology holder countries if and when the reliability and competitiveness of fast reactors will be proved, or to continue with predominantly LWRs in the opposite case.

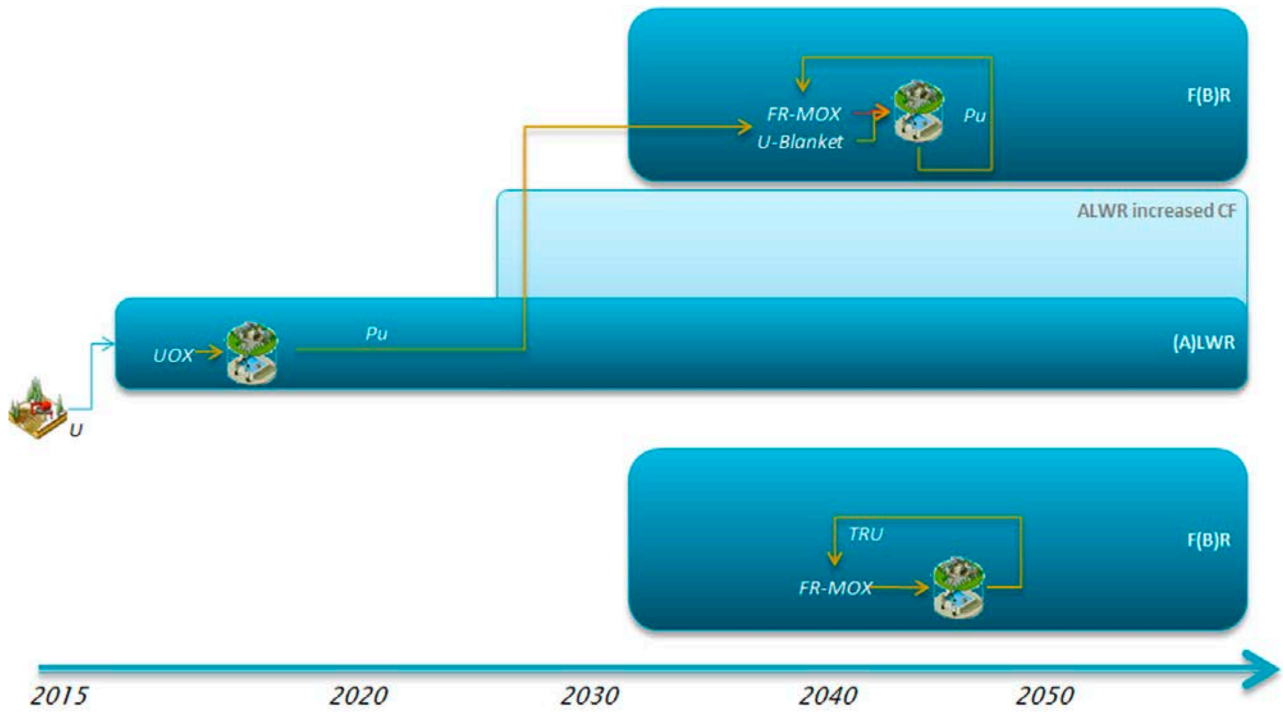
In scenarios with a few fast reactors, the following two options are considered:

(a) Fast reactors providing support to continued MOX fuel recycling in LWRs (where fast reactors provide the additional plutonium vector required to top up the isotopically degrading plutonium vector from LWRs);
(b) Scenarios where fast reactors help to ‘absorb’ the plutonium inventory from LWR used fuel both, already accumulated, as well as being produced by the operating LWRs.

Case studies representing the scenarios of the B family are presented in Section 3.3.

2.7.4. Fast reactor centred scenarios enveloping scenarios with reprocessing of thermal reactor fuel to enable noticeable growth rate of fast reactor capacity (Scenario family C)

Fast reactor centred scenarios are scenarios with reprocessing of thermal reactor fuel to enable noticeable growth rate of fast reactor capacity (Scenario family C, see Fig. 2.11). These scenarios do not develop through a LWR MOX phase, though it is not excluded as such. In scenarios of the C family, fast reactors perform as plutonium balance systems allowing to deploy the desired numbers of thermal and fast reactors, while minimizing



Note: ALWR — advanced light water reactor; CF — conversion factor; FBR — fast (breeder) reactor; LWR — light water reactor; MOX — mixed oxide; TRU — transuranic; UOX — uranium oxide.

FIG. 2.11. Fast reactor centred scenarios — scenarios with reprocessing of thermal reactor fuel to enable noticeable growth rate of fast reactor capacity (Scenario family C).

the separated plutonium inventories to a bare minimum needed for nuclear power plant operation in a closed nuclear fuel cycle [2.6].

Given the present day expected deployment of nuclear energy in most countries and the current knowledge on occurrence of natural uranium, there may be no real need to deploy a significant number of fast reactors before the mid century for reasons of shortage in natural uranium [2.34]. But there is a real need to address the back end fuel cycle issue of piling up used fuel inventories. This makes it necessary to ensure the continued proper management of plutonium which, one day, may require the introduction of fast reactors to continue its recycle in mixed LWR and fast reactor parks.

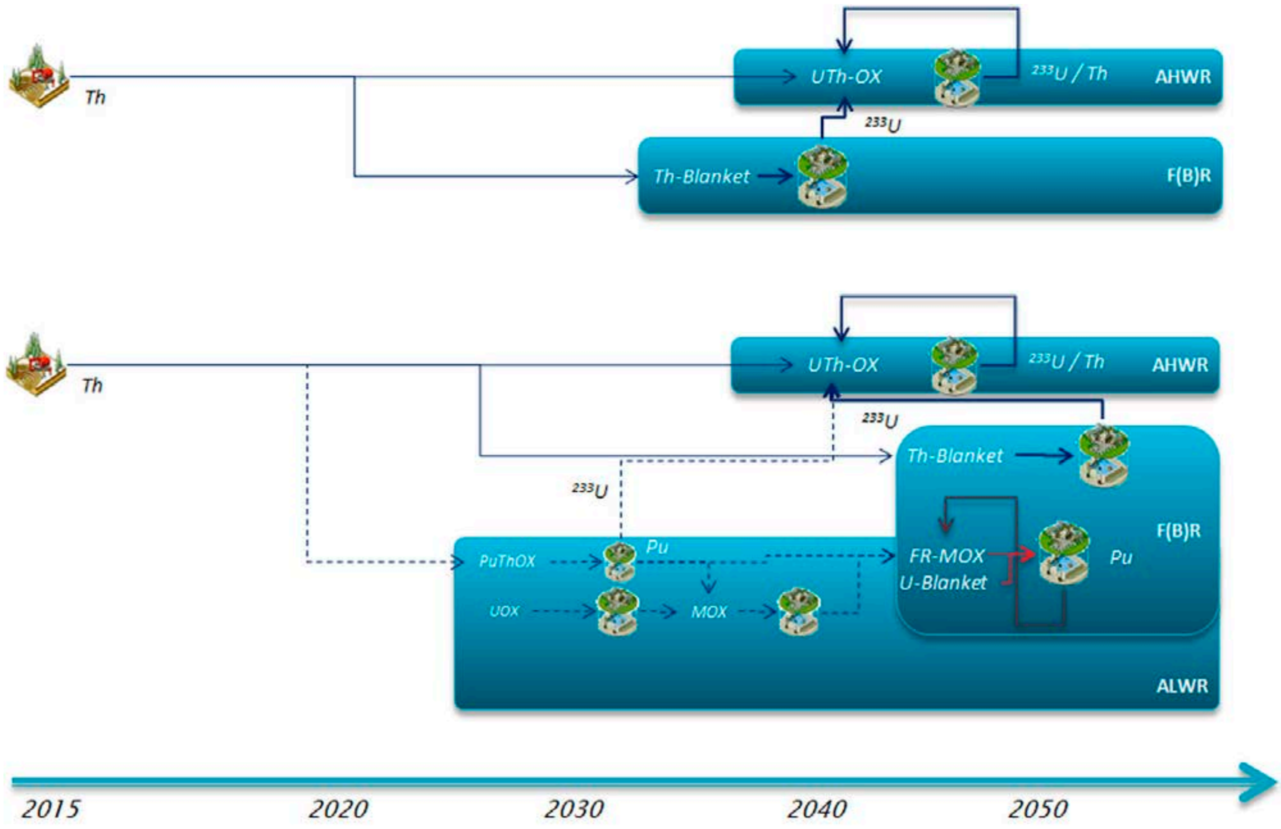
One of the objectives of the scenarios of the C family is to ramp up the introduction of fast reactors through multi-recycling of plutonium or even breeding. In this way one can drastically reduce the natural uranium/TW·h consumption for a reactor park, once a certain scarcity in natural uranium occurs or when an increased independence on the front end fuel cycle services would be required. The various possible scenarios belonging to the C family are analysed in detail in Section 3.4.

2.7.5. Scenarios of transition to Th/^{233}U fuel cycle and scenarios with alternative U/Pu/Th fuel cycles (Scenario family D)

With India[7] being a prime example, for a variety of reasons countries may also seek to deploy or co-deploy a thorium based NES. This may provide even more extensive fissile resources than the present day uranium/plutonium cycle can offer [2.21][8] and could also secure independence from foreign supplies of fissile material [2.35–2.39]. As natural thorium contains no fissile isotopes, the following two strategies are being considered for a transition to the thorium/^{233}U fuel cycle, see Fig. 2.12:

[7] See www.world-nuclear.org/information-library/country-profiles/countries-g-n/india.aspx

[8] Thorium is theoretically around four times more abundant than natural uranium; however, natural thorium contains no fissile isotopes [2.25].



Note: ALWR — advanced light water reactor; F(B)R — fast (breeder) reactor; LWR — light water reactor; MOX — mixed oxide; UOX — uranium oxide.

FIG. 2.12. Scenarios of transition to Th/^{233}U fuel cycle and scenarios with alternative U/Pu/Th fuel cycles (Scenario family D).

(a) Breeding of ^{233}U in thorium blankets of uranium–plutonium fuelled fast reactors with its subsequent use in thermal spectrum HWRs or LWRs. This option requires a closed nuclear fuel cycle for both thorium/^{233}U and uranium–plutonium fuel.

(b) Uranium-233 in situ breeding and burning in fertile zones of heterogeneous cores of advanced HWRs or LWRs, with their fissile zones being fuelled by enriched uranium or uranium–plutonium fuel (e.g. MOX). This option, securing only a partial transition to energy production from thorium/^{233}U fuel (up to 40–50% [2.29]), can be realized within a once through nuclear fuel cycle.

The scenarios of the D family are analysed in the case studies presented in Section 3.5.

2.8. DRIVERS AND IMPEDIMENTS TO PURSUE A PARTICULAR NUCLEAR ENERGY SCENARIO FAMILY

Technical meetings and case studies[9] of the SYNERGIES collaborative project made it possible to identify drivers and impediments for considering a particular scenario family[10], as well as possible patterns of collaboration among countries in these scenarios. These 'scenario specific' drivers and impediments are briefly summarized below for each scenario family as introduced in Section 2.7. The drivers and impediments for collaboration among countries to amplify the benefits of each scenario family by bringing them to those technology users and newcomers who would not pursue technical innovations indigenously are then described in Section 4. Section 4

[9] Case studies of the SYNERGIES project are presented in Section 3.

[10] Relationship between scenario families and options for enhanced nuclear energy sustainability is explained in Table 2.2.

also incorporates major findings of the fourth INPRO Dialogue Forum, on drivers and impediments for regional cooperation on the way to sustainable NESs, convened in Vienna in 2012.[11]

2.8.1. Business as usual scenarios consisting of once through fuel cycle and mono-recycling of U/Pu in thermal spectrum reactors (Scenario family A), with reference to Section 2.7.2 and Figs 2.7–2.9

At present, most of the Member States having a nuclear energy programme operate with thermal reactors with uranium dioxide fuel in a once through fuel cycle. Such situation is reasonably stable (to the extent some call it sustainable in the short term), owing to the following factors:

— The perceived no immediate shortage of natural uranium;
— Economic competitiveness in the short term with reliance on the available competitive offers of front end fuel cycle services;
— Competitive globally available services for wet and dry interim storage construction;
— No need to develop additional domestic specialized skills related to back end fuel cycle services.

On the other hand, there are factors that make the current situation non-sustainable from a resource and waste perspective, including:

— Growing security of supply risks in the long term.
— Spent fuel accumulation that is directly proportional to energy produced by nuclear power plants:
  - Saturation of the available wet spent fuel pool capacities for interim (cooled) storage.
  - Limitations of the interim dry spent fuel storage facilities: long term/very long term behaviour of spent fuel in dry storage is unknown and may reduce options for further management of such fuel even in the medium term (i.e. beyond a certain interim storage period no options may remain to manage spent nuclear fuel); in this, the associated increased costs and risks cannot be assessed up front.
— Proliferation and security risks associated with long term/very long term interim storage and direct disposal of spent nuclear fuel.

The above mentioned factors could lead to certain kinds of synergistic collaboration among countries, which may include:

— Regional interim storage and geological disposal sites [2.9][12];
— Front end regional fuel cycle centres (e.g. URENCO).

Scenario family A also includes scenarios with mono-recycling of plutonium in LWRs. Already a reality in the European Union, although on a limited scale [2.28, 2.29], this step is driven by:

— The possibility to reduce natural uranium specific consumption by 15–25% for the case of uranium and plutonium recycling;
— An option to empty on-site and off-site wet interim spent fuel storage pools;
— An option to postpone the need for wet/dry interim (regional) spent fuel storage solutions, as well as the need for geological disposal;
— Alleviation of difficult to safeguard proliferation risks in geological disposal;
— Possibility to rely on the available, although limited, international/regional back end fuel cycle services.

The impediments for the above mentioned scenarios are as follows:

— Their realization requires at least a medium term vision on nuclear energy use, which is not yet developed in many Member States.

[11] See www.iaea.org/INPRO/4th_Dialogue_Forum/index.html
[12] They do not yet exist.

— If the domestic recycling is considered, this would require careful planning to align the spent fuel reprocessing and the uranium and plutonium recycling requirements, which might be difficult to achieve in some countries.
— Notwithstanding the fact that international services are available, these scenarios will require certain fuel cycle management skills to be developed domestically.
— Yet another impediment could be the agreement a country may have with another country, under which certain restrictions on nuclear trade with the third parties are imposed.

2.8.2. Scenarios with the introduction of a number of fast reactors to support multi-recycling of Pu in LWRs and fast reactors (Scenario family B), with reference to Section 2.7.3 and Fig. 2.10

These scenarios may be driven by:

— Avoidance of any spent fuel direct disposal;
— Possibility to further reduce specific natural uranium consumption;
— Delayed interim storage needs for MOX spent fuel;
— Avoidance of fissile material disposal, possibly simplifying safeguards and physical protection requirements for such disposal sites.

However, the impediments here relate to:

— The increase of the specific fraction of minor actinides in ultimate waste;
— The need to develop a well defined back end fuel management strategy;
— The need to modify core management schemes for evolutionary LWRs;
— The need to demonstrate fast reactor technology and the associated fuel cycle.

The synergistic collaborations for the Scenario family B may include:

— Regional interim storage and geological disposal sites;
— Regional fuel cycle centres (e.g. La Hague);
— Pre-cycling and TOP-MOX (see Figs 2.8 and 2.9), as well as other international (regional) fuel cycle services.

The scenarios of the B family could substantively address the spent fuel buildup issue, but will provide only limited improvement in natural fissile resource saving. It could be noted that these scenarios can be viewed as a transition phase towards fast reactor centred scenarios of the C family, which offer much better natural uranium savings but would require a larger number of fast reactors.

2.8.3. Fast reactor centred scenarios enveloping scenarios with reprocessing of thermal reactor fuel to enable noticeable growth rate of fast reactor capacity (Scenario family C), with reference to Section 2.7.4 and Fig. 2.11

Scenarios with a higher fraction of fast reactors may be driven by rapidly growing NESs and/or when it is strategically decided by a country to pursue energy independence including both, fissile resource and sustainable waste management. The technologies for such scenarios are available and are (almost) industrially mature in several technology holder countries.

From the investment standpoint, fast reactor centred scenarios make sense only when the targeted deployment scale of fast reactors is several tens of gigawatts within the present century; otherwise, the payback period may well exceed the century time frame [2.6]. However, countries with smaller nuclear demand projections could share the benefits offered by such scenarios through synergistic collaboration with technology holders in fuel cycle back end (see Section 2.5). The drivers for embarking on such scenarios are:

(a) Possibility to achieve a ‘perfect synergy’ between LWRs/HWRs and fast reactors (i.e. recycle all mined uranium resources and tails within a single multicomponent NES).
(b) High degree of flexibility, given multiple parameters:

— Fast reactor/LWR+HWR ratio;
— Fast reactor conversion/breeding ratio;
— Reduced specific (per unit of energy produced) minor actinide inventory in waste.

(c) Reduction/elimination of proliferation risks related to final disposal of waste and, for some options, to enrichment.

At the same time, moving along such scenarios is restricted by the following impediments:

— Anticipated higher overnight construction costs for fast reactors;
— The need to achieve industrial maturity for fast reactors and the associated fuel cycles;
— Synergistic collaboration in scenarios of the C family might require both, commonly shared vision of an international (regional) NES and regional fast reactor fuel cycle service centres, which in turn would require time to be developed and deployed; ideally, an alignment on main fuel cycle technology choices would be an asset here.

Multiple variants can be considered within this scenario family, depending on the timing of introduction of fast reactors and the ratio of fast reactor/LWR deployment in a variety of national or regional nuclear power park settings. Fast reactor deployment could be considered domestically for large enough nuclear energy programmes [2.6]; however, due to technical–economic and sociopolitical reasons, preference may be eventually given to international consortia where fast reactors are part of the regional fuel cycle centres aimed at managing the plutonium balance for many countries, possibly complementing the system also with reprocessed uranium and plutonium recycling in LWRs and even HWRs.

2.8.4. Scenarios of transition to Th/^{233}U fuel cycle and scenarios with alternative U/Pu/Th fuel cycles (Scenario family D), with reference to Section 2.7.5 and Fig. 2.12

With regard to Scenario family D, the case studies presented in Section 3 do not address synergistic collaborations among technology holders and technology users/newcomers for the plain reason that so far there is only one country — India — that has moved significantly along the thorium route to cater to the needs of its huge domestic market in a sovereign manner. Notwithstanding, the discussions at the SYNERGIES technical meetings make it possible to assume that the drivers for synergistic collaboration in scenarios of the D family could be:

— Full realization of nuclear energy sustainability potential, additionally boosted by the several times increase of the available natural fissile/fertile resources;
— Possibility to exploit in full the synergistic potential among thermal spectrum and fast spectrum reactors with respect to thorium and ^{233}U.

The impediments for embarking upon scenarios of the D family are as follows:

— Addition of the ^{233}U–thorium fuel cycle would result in a more complex fuel cycle management involving both the uranium and plutonium and the ^{233}U and thorium cycle simultaneously.
— Also required would be a whole new nuclear fuel cycle infrastructure specific to ^{233}U and thorium, including mining, new fuel and fuel fabrication technologies, new fuel handling and radioprotection technologies, new separation processes and waste characterizations. Overall, qualification of the whole technology towards industrialization would be required.

The synergistic collaborations possible for scenarios of the D family could be:

— Regional interim storage and geological disposal sites;
— International/regional nuclear power plant parks and fuel cycle services.

Some observers to the SYNERGIES project also considered examining the potential of thorium–rare earth synergy (thorium is a by-product of rare earth mining). It was noted that here the economics might either be a driver (competitive) or an impediment (non-competitive).

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3. SYNERGIES SCENARIO CASE STUDIES

The Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES) scenario case studies can be grouped according to the following families of reactor and fuel cycle scenario families used in the analysis (A, B, C and D):

(a) Scenario family A: Business as usual scenarios consisting of once through fuel cycle and mono-recycling of U/Pu in thermal spectrum reactors (see Annexes I–VI, XX, XXII and XXVII).
(b) Scenario family B: Scenarios with the introduction of a number of fast reactors to support multi-recycling of Pu in LWRs and fast reactors (see Annexes VII and VIII).
(c) Scenario family C: Fast reactor centred scenarios enveloping scenarios with reprocessing of thermal reactor fuel to enable noticeable growth rate of fast reactor capacity (see Annexes I, IX–XV, XVII–XIX, XXI, XXIII, XXIV and XXVI).
(d) Scenario family D: Scenarios of transition to Th/^{233}U fuel cycle and scenarios with alternative U/Pu/Th fuel cycles (see Annex XV).

The study summaries are structured as follows:

(1) Introduction:
- Background and previously performed studies;
- Relevance to the objective of SYNERGIES and SYNERGIES Tasks 1–4;
- Where to find the complete case study (Annex #).

(2) Objective and problem formulation:
- Provide the objective of the case study;
- Formulate the questions to be answered;
- Formulate the problem by describing the issues addressed by the case study.

(3) Assumptions, methods, codes and input data used:
- All important assumptions and simplifications need to be mentioned;
- To be described in short with a reference to more detailed description in the annex.

(4) Summary presentation and analysis of the results:
- Tables, graphs and minimum necessary text presenting the results of the study, considered the most representative for the case study declared objective;
- Short explanation of the results;
- Any additional, but necessary, comments on the results are briefly included;
- To be mentioned: the more detailed analysis included in the corresponding annex.

(5) Conclusions:
- Main conclusions of the case study, presented as a summary;
- How these conclusions relate the objective of SYNERGIES and SYNERGIES Tasks 1–4;
- To be mentioned: the complete presentation of the case study conclusions in the corresponding annex.

Table 3.1 compiles the study attributes and includes the following:

(i) Study title and relevance to the objective of SYNERGIES Tasks 1–4.
(ii) Scenario level: global, regional or national.
- According to the Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS), a framework homogeneous world model is used for global scenarios and heterogeneous geographical or non-geographical world model for regional scenarios. Non-geographical heterogeneous world model based on groups of different countries having different policies regarding fast reactors and fuel cycle back end. Region and country specific cases also belong here.

(iii) Information on category of synergies examined: technology only and/or technology and international cooperation with regard to the nuclear fuel cycle of country/region.

— Synergies in technology: synergies among technologies with certain complementarity between fuel cycles of different reactors on a purely technical level. For example, reprocessed fuel from thermal reactors could be used to produce fuel loads for fast reactors — ‘could’, but not necessarily ‘will’.
— Synergies in collaboration: synergistic collaboration among countries based on certain arrangements. For example, arrangements for sending thermal reactor spent fuel to those countries where, in the future, possibly, it could be reprocessed in regional centres for the purpose of further use in fast reactors or in light water reactors (LWRs).

(iv) Material flow analysis only and/or material flow analysis and economics.
— Material flow analysis includes analysis of key indicators in the following areas: power production; nuclear material resources; discharged fuel; radioactive waste and minor actinides; fuel cycle services; and material balances.

(v) Country and Annex # with detailed information on the study.

3.1. BUSINESS AS USUAL SCENARIOS CONSISTING OF ONCE THROUGH FUEL CYCLE AND MONO-RECYCLING OF U/Pu IN THERMAL SPECTRUM REACTORS (SCENARIO FAMILY A)

3.1.1. National Argentine scenario with cooperation options

3.1.1.1. Introduction

Argentina’s National Atomic Energy Commission (Comisión Nacional de Energía Atómica, CNEA) advises the Executive on the definition of the nuclear policy oriented towards the peaceful uses of nuclear energy. Established in 1950 as part of a process of industrialization promoted by the State, it was intended from the beginning that Argentina would not only be a nuclear technology user but also a nuclear technology holder.

Argentina was the first country in its region to operate an experimental nuclear reactor, the RA-1, which achieved first criticality in January 1958 and produced the first national radioisotopes for medical and industrial use. With this experience and knowledge acquired, Argentina was able to realize other larger enterprises, such as the RA-3 and RA-6 and others exported to Algeria, Australia, Egypt and Peru. Moreover, in 1974 the CNEA began operating the Atucha I nuclear power plant (central nuclear Atucha I, CNA I), the first nuclear power plant in Latin America.

Nuclear infrastructure development during 1970–1989 was mainly focused on the front end of the nuclear fuel cycle, including the development of new uranium deposits, the operation of uranium concentrate purification and uranium dioxide production plants, the construction of a facility to supply fuel elements for operating nuclear power plants, the implementation of a special alloy facility dedicated mainly to the production of zircaloy pods and components for the fuel elements, and the development of technology for uranium enrichment by the gaseous diffusion method. During this period a second plant, the Embalse nuclear power plant (central nuclear Embalse, CNE), was also constructed and began operating in January 1984. The construction of a third nuclear power plant (CNA II) was initiated in 1981, but it experienced significant delays due to financial conditions; all construction works were halted during the1990s. With regard to the back end of the nuclear fuel cycle, reprocessing activities in Argentina began in the 1960s. During the 1970s and 1980s, several projects reached different levels of progress.

In August 2006, the Government announced a decision to reactivate nuclear activities in the country, which included the establishment of a nuclear programme for the short and medium term, based on developing applications of nuclear technology for public health and industry, as well as increasing the role of nuclear power in the national energy mix by:

— Completion of CNA II;
— Life extension of CNE;
— Start of preliminary feasibility studies for the construction of a fourth nuclear power plant;
— Completion of feasibility studies for the construction of the nationally designed modular central prototype, a low capacity (25 MW(e)) reactor called CAREM (Central ARgentina de Elementos Modulares), according to the laws 25064, 25160 and 26566;
— Recovery of fuel cycle activities that were suspended, including uranium exploration, mining and enrichment.

TABLE 3.1. SUMMARY TABLE OF STUDIES AND THEIR ATTRIBUTES

Study	Global, regional, national	Relevance to Tasks 1–4	Synergies in		Material flow analysis	Economics	Annex, country
			Technology	Collaboration			
3.1. Business as usual scenarios consisting of once through fuel cycle and mono-recycling of U/Pu in thermal spectrum reactors (Scenario family A)							
3.1.1. National Argentine scenario with cooperation options	N	1	–	+	+	–	VI, Argentina
3.1.2. Assessment of impact of fuel cycle back end options on levelized unit electricity cost of produced electricity based on nuclear fuel cycle in Armenia	N	1	–	+	+	+	I, Armenia
3.1.3. Economic value of uranium recovered from LWR spent fuel as fuel for HWRs	R	1	+	–	+	+	III, Canada
3.1.4. A reactor synergy: using HWRs to transmute Am from LWR spent fuel	G/R	3	+	–	+	+	XXVII, Canada
3.1.5. 'EU27 scenario' with the extended use of regional fuel cycle centre composed of the La Hague and MELOX facilities		1					IV, France
3.1.6. Comparative assessment of collaborative fuel cycle options for Indonesia	N	1	+	+	+	–	II, Indonesia
3.1.7. Analysis of ALWR based scenario	G/R	2	+	+	+	–	XX, Japan
3.1.8. National Romanian scenarios with reliance on domestic and imported U/ fuel supply, by considering regional collaboration in nuclear fuel cycle and including economic analysis	N	1	–	+/–	+	+	V, Romania
3.1.9. Scenarios with replacement heat generation	N	2	+	+	+	+	XXII, Ukraine
3.2. Scenarios with the introduction of a number of fast reactors to support multi-recycling of Pu in LWRs and fast reactors (Scenario family B)							
3.2.1. Evaluation of national NESs based on Pu cycle with the introduction of a number of fast reactors	N	1	+	+	+	–	VII, INPRO/IAEA, France, Russian Fed.

TABLE 3.1. SUMMARY TABLE OF STUDIES AND THEIR ATTRIBUTES (cont.)

Study	Global, regional, national	Relevance to Tasks 1–4	Synergies in		Material flow analysis	Economics	Annex, country
			Technology	Collaboration			
3.2.2. Global scenarios with the introduction of a number of fast reactors under uncertainties in the scale of nuclear energy demand and in the nuclear power structure	R	1	+	+	+	+	VIII, INPRO/IAEA, Russian Fed.
3.3. Fast reactor centred scenarios enveloping scenarios with reprocessing of thermal reactor fuel to enable noticeable growth rate of fast reactor capacity (Scenario family C)							
3.3.1. Summary of EU scenarios with transmutation option for nuclear phase out and continued nuclear scenarios	R	3	+	+	+	+	XXIV, Belgium
3.3.2. Preliminary analysis of the nuclear energy development scenarios based on U–Pu multi-recycling in China	N (not reflecting national policy)	1	–	–	+	–	X, China
3.3.3. Studies of minor actinide transmutation in SFRs	N (not reflecting national policy)	3	+	–	+	–	XXVI, China
3.3.4. A French study on radioactive waste transmutation options	N	3	+	+	+	+	XXIII, France
3.3.5. Comparative economic analysis of selected synergistic and non-synergistic GAINS scenarios	G/R	1	+	+	+	+	XVII, INPRO/IAEA
3.3.6. Sensitivity analysis of the shares of NG1/NG2/NG3 country groups in GAINS scenarios	G/R	1	+	+	+	–	XIV, XV, INPRO/IAEA, Russian Fed.
3.3.7. Alternative deployment strategy of fast reactor startup on enriched U fuel	G	2	+	+	+	+	XVIII, XIX, INPRO/IAEA, Russian Fed.
3.3.8. Sustainable regional scenario with ‘adiabatic’ lead fast reactors in selected countries	R	1	+	+	+	+	IX, Italy
3.3.9. Long term scenario study for nuclear fuel cycle in Japan	N	1	+/–	–	+	–	XI, Japan

TABLE 3.1. SUMMARY TABLE OF STUDIES AND THEIR ATTRIBUTES (cont.)

Study	Global, regional, national	Relevance to Tasks 1–4	Synergies in		Material flow analysis	Economics	Annex, country
			Technology	Collaboration			
3.3.10. Modelling of regional collaborative deployment scenarios aimed at solving the problem of accumulating spent nuclear fuel inventory	R/N	1	+	+	+	+	XII, XIII, I, Russian Fed., Ukraine, Armenia
3.3.11. Homogeneous and heterogeneous world model scenarios with WWER-Ss, SMRs and HTRs, including non-electrical applications	G/R	2	+	+	+	−	XXI, Russian Fed.
3.3.12. Analysis of advanced European scenarios including transmutation and economical estimates	R	3	+	+	+		XXV, Spain
3.3.13. Scenario with the WWER–fast reactor collaborative deployment	N	1	+	+	+	+	XIII, Ukraine
3.4. Scenarios of transition to Th/^{233}U fuel cycle and scenarios with alternative U/Pu/Th fuel cycles (Scenario family D)							
3.4.1. Evaluation of a scenario of transition to Th/^{233}U fuel cycle	N (not reflecting national policy)	1	+	−	+	−	XVI, India
3.4.2. Summary of INPRO studies on global scenarios with introduction of Th	G/R	2	+	+	+	+	INPRO/IAEA

Note: ALWR — advanced light water reactor; GAINS — Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle; HTR — high temperature reactor; HWR — heavy water reactor; INPRO —International Project on Innovative Nuclear Reactors and Fuel Cycles; LWR — light water reactor; NES — nuclear energy system; SFR — sodium cooled fast reactor; SMRs — small and medium sized reactors; WWER — water cooled, water moderated power reactor.

In 2008, the CNEA instructed to restart activities to recover the ability to reprocess spent fuel. Given the possibility of having facilities suitable for hot process development on a small scale, these objectives were included in the Strategic Plan 2010–2019.

There are many achievements and activities relevant to nuclear energy development in Argentina; more information about historical nuclear development is chronologically detailed in the IAEA Country Nuclear Power Profiles.[1] It should be mentioned that during the last sixty years, Argentina has gained vast experience in the nuclear area which can be shared at the regional and global level. In this context, the CNEA participates in the SYNERGIES project performing scenarios at the national and regional level, and identifying those areas in which help from other countries is needed for development of the national nuclear plan, and those areas in which Argentina can assist other countries with the similar goals. Although the project presents a regional analysis (Argentina was the only Latin American participant in the SYNERGIES project), local development strategies and possible areas for international cooperation are examined from a local perspective.

[1] See https://cnpp.iaea.org/countryprofiles/Argentina/Argentina.htm

The development of scenarios in which fast reactors are incorporated into the nuclear matrix has been considered in the SYNERGIES project by the participating countries that are currently developing, or envisaging use of, this technology. However, since it is of national interest to consider all nuclear technology options available for the future, the Argentina country case also analyses the types of fast reactor technology that could be included in Argentina's nuclear matrix in the future, in accordance with the CNEA Strategic Plan. The complete case study can be found in Annex VI on the CD-ROM accompanying this publication.

3.1.1.2. Objective and problem formulation

Argentina's contribution to the SYNERGIES project consists in performing two scenarios for nuclear power expansion at the national level, with the aim of exploring the requirements for nuclear power plants and fuel cycle facilities from 2013 to 2050. As a complement, a comparative evaluation of Generation IV reactors is performed, with the aim of defining the Generation IV reactor types of most interest to the country. Another goal of the case study is to identify potential areas of cooperation in the region, highlighting the current support of Argentina's nuclear development in other countries and how it could be increased in the future.

3.1.1.3. Assumptions, methods, codes and input data used

The role of nuclear energy in Argentina's energy mix was assessed according to the assumption that nuclear energy will supply about 30% of future national energy demand, the rest being supplied as follows: 30% by thermal fossil power plants, 30% by hydropower plants and 10% by other renewables.

Two scenarios of final energy demand were developed. For both scenarios, demand projections until 2030 take into account modelling of the current Argentina's electricity sector in the medium term. Then, to achieve the values projected until 2050, the demand was raised with respect to world average projections in terms of energy/capita, according to the projections of the International Energy Agency and UN demographic projections for Argentina [3.1]. The share of nuclear energy in the low scenario is calculated considering a scenario of minimum electrical demand. The higher nuclear participation scenario is calculated with the values of the high electrical demand scenario.

In the short term, the current plans and recent announcements made in 2013 by the Ministry of Federal Planning, Public Investment and Services were taken into account with regard to capacity, and tentative data up to 2023 were followed. In both scenarios, the following assumptions are considered:

— Commissioning of CNA II (pressurized heavy water reactor, PHWR);
— Refurbishment and life extension of CNE (PHWR);
— Construction and connection to the grid of CAREM-25 (integrated pressurized water reactor, PWR);
— Life extension of CNA I;
— Commissioning of a CAREM-150 (integrated PWR);
— Construction of the fourth nuclear power plant (two modules of 0.75 GW(e), PHWR);
— Construction of the fifth nuclear power plant (one or two modules of 1.2 GW(e), PWR);
— Definitive shutdown of CNA I and CNE in 2046 and 2050, respectively.

It is assumed that from 2023 only LWRs would be commissioned. Each scenario includes a different number of PWRs and CAREM-150s. Projections are based on the premise that Argentina will continue its development and implementation of national nuclear technology. Accordingly, almost the same number of nationally designed and constructed CAREM-150s is expected for both considered scenarios with regard to the participation of nuclear energy in the national energy mix.

3.1.1.4. Summary presentation and analysis of the results

Table 3.2 shows the two projections for evolution of nuclear power capacity, with details on the input/output of nuclear power, the annual balance accumulated and the share of nuclear energy in electricity demand.

TABLE 3.2. NUCLEAR POWER SHARE AND EVOLUTION OF THE INSTALLED CAPACITY BY SCENARIO

Year	Low projection of nuclear power capacity				High projection of nuclear power capacity			
	Share of nuclear energy in electricity demand (%)	Nuclear power (added capacity, GW(e))	Nuclear power (removed capacity, GW(e))	Nuclear power balance (GW(e))	Share of nuclear energy in electricity demand (%)	Nuclear power (added capacity, GW(e))	Nuclear power (removed capacity, GW(e))	Nuclear power balance (GW(e))
2010	7.2	1.005		1.005	7.2	1.005		1.005
2011	6.7			1.005	6.7			1.005
2012	6.5			1.005	6.5			1.005
2013	6.4	0.005		1.010	6.3	0.005		1.010
2014	6.8	0.745	0.648	1.107	6.6	0.745	0.648	1.107
2015	8.7	0.342		1.449	8.4	0.342		1.449
2016	10.5	0.341		1.790	10.1	0.341		1.790
2017	10.3			1.790	9.8			1.790
2018	10.2	0.025		1.815	9.7	0.025		1.815
2019	8.0		0.362	1.453	7.6		0.362	1.453
2020	12.6	0.900		2.353	11.9	0.900		2.353
2021	14.3	0.362		2.715	13.4	0.362		2.715
2022	17.9	0.750		3.465	16.6	0.750		3.465
2023	23.7	1.200		4.665	21.8	1.200		4.665
2024	23.2			4.665	21.2			4.665
2025	22.8			4.665	26.0	1.200		5.865
2026	22.4			4.665	25.3			5.865
2027	22.7	0.150		4.815	25.3	0.150		6.015
2028	22.3			4.815	24.7			6.015
2029	21.9			4.815	24.1			6.015
2030	21.5			4.815	28.2	1.200		7.215
2031	21.0			4.815	27.8			7.215
2032	20.7			4.815	27.9	0.150		7.365
2033	25.4	1.200		6.015	27.5			7.365
2034	25.7	0.150		6.165	27.0			7.365
2035	25.3			6.165	30.9	1.200		8.565
2036	24.9			6.165	30.5			8.565
2037	24.6			6.165	30.6	0.150		8.715
2038	24.2			6.165	30.1			8.715
2039	23.9			6.165	29.7			8.715
2040	23.5			6.165	33.2	1.200		9.915
2041	23.6	0.150		6.315	32.6			9.915

TABLE 3.2. NUCLEAR POWER SHARE AND EVOLUTION OF THE INSTALLED CAPACITY BY SCENARIO (cont.)

Year	Low projection of nuclear power capacity				High projection of nuclear power capacity			
	Share of nuclear energy in electricity demand (%)	Nuclear power (added capacity, GW(e))	Nuclear power (removed capacity, GW(e))	Nuclear power balance (GW(e))	Share of nuclear energy in electricity demand (%)	Nuclear power (added capacity, GW(e))	Nuclear power (removed capacity, GW(e))	Nuclear power balance (GW(e))
2042	23.2			6.315	32.5	0.150		10.065
2043	27.1	1.200		7.515	32.0			10.065
2044	26.7			7.515	31.4			10.065
2045	26.2			7.515	34.6	1.200		11.265
2046	24.6		0.362	7.153	33.0		0.362	10.903
2047	24.2			7.153	32.9	0.150		11.053
2048	24.3	0.150		7.303	32.4			11.053
2049	23.9			7.303	31.9			11.053
2050	21.3		0.683	6.620	29.5		0.683	10.370

(a) Uranium requirements for nuclear expansion 2013–2050

For operating nuclear power plants and nuclear projects included in the scenarios of electricity system expansion, future requirements o f natural uranium were examined. For the existing CNA I and CNE, 35 t U per year and 85 t U per year are required, respectively. CNA II will begin operating with natural uranium and an annual requirement of 92 t U is expected. For the fourth nuclear power plant, if considering two reactors of 0.75 GW(e) each, about 81 t U per year will be required for each, while the 1.2 GW(e) reactors will each require about 216 t of natural uranium per year. For CAREM-25, 5 t of annual consumption of natural uranium is estimated, while for CAREM-150 approximately 27 t U are required for each.

The accumulated natural uranium requirement for the low scenario would amount to approximately 26 775 t U by 2050, while for the high scenario the accumulated requirement would be of about 37 390 t U. Natural uranium requirements were calculated taking a value of 4% enrichment for the PWRs — considering that starting from 2023, it is assumed that this type of reactor could enter into operation. Figure 3.1 presents the natural uranium annual requirements for the nuclear power plants and the corresponding accumulations for both scenarios.

(b) Generation IV nuclear reactors: Argentina comparative assessment

The Generation IV International Forum (GIF) project has selected six nuclear reactor concepts (the Generation IV reactors) which meet the set forth requirements of safety and reliability, economic efficiency and competitiveness, sustainability (efficient use of uranium reserves and minimization of nuclear waste) and proliferation resistance [3.2]:

— Sodium cooled fast reactor (SFR);
— Lead cooled fast reactor (LFR);
— Gas cooled fast reactor (GFR);
— Supercritical water cooled reactor (SCWR), in its fast (F) and thermal (T) versions;
— Very high temperature reactor (VHTR);
— Molten salt reactor (MSR).

The methodology used to perform the comparative evaluation of these concepts is inspired by Ref. [3.3], developed by the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). This methodology is based on the estimation of a set of requirements called ‘indicators’, which are the selected parameters to evaluate the performance of a nuclear energy system (NES) in a particular area of interest. The following areas of interest were selected to evaluate the reactors (see Fig. 3.2 for the ratings):

— Feasibility of the concept;
— Design and nuclear safety;
— Economy;
— Sustainability;
— Proliferation resistance;
— Fuels;
— Reprocessing;
— Materials;
— Balance of plant.

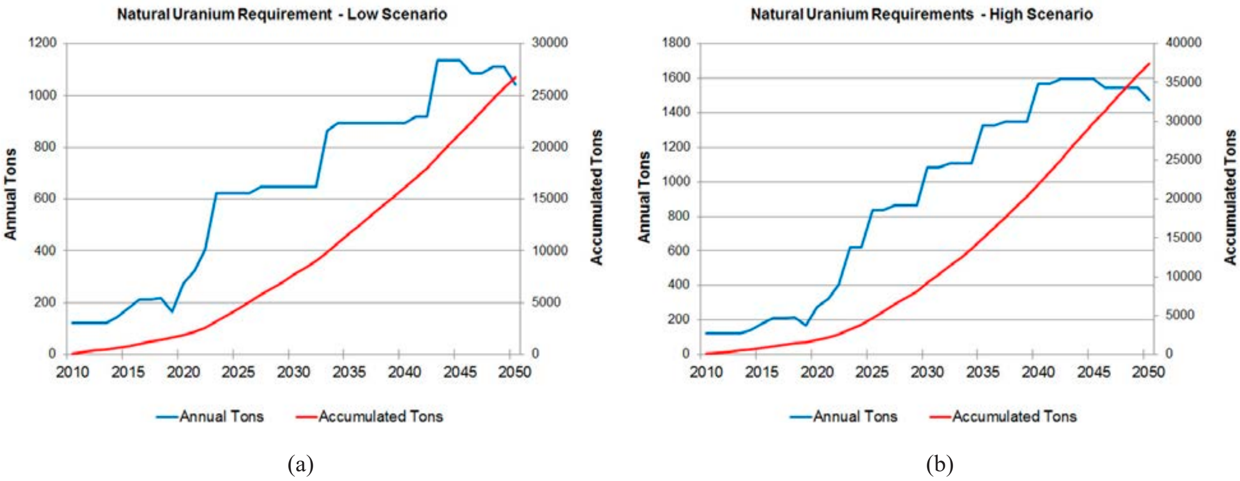

FIG. 3.1. Natural uranium annual and accumulated requirements (a) low scenario and (b) high scenario.

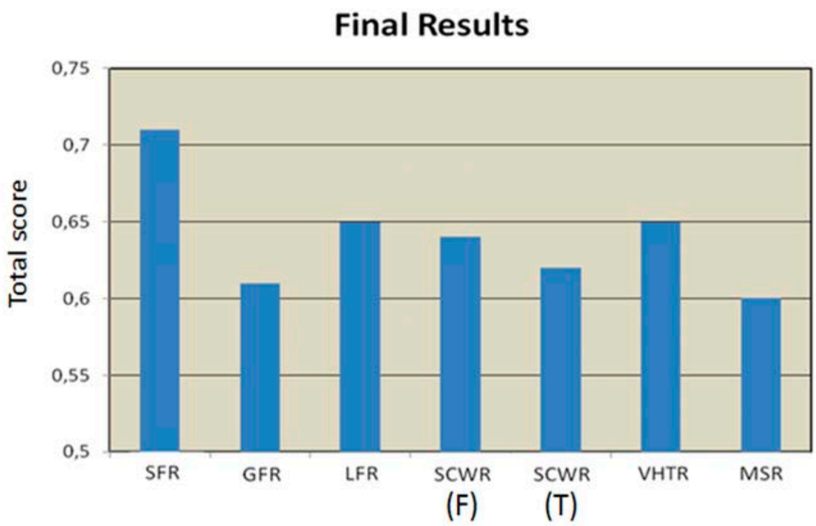

FIG. 3.2. Final results: Comparison between Generation IV reactors.

All the concepts assessed have a good overall performance. The highest score corresponds to SFRs. Their overall performance was better than the rest of the GIF concepts, based on the widest operational experience and excellent sustainability characteristics.

The second highest score corresponds to LFRs and VHTRs. In the case of LFRs, there is a significant number of ongoing related R&D projects, including plans to build prototype reactors in the medium term.[2] For VHTRs, this score is achieved owing mostly to the excellent performance foreseen for its fuel and its rapid response capability to mitigate severe accidents. However, since it is a thermal reactor, VHTR performance in the area of sustainability is lower than LFRs, taking into account that VHTRs assure a poorer use of the natural resources of fissile materials due to its lower conversion factor. The major interest in this reactor is due to the high temperature of gas released from the primary circuit, which enables its use for hydrogen production and processes that require high temperatures.

The third highest score is assigned to SCWR(F). They have an average performance with respect to most of the concepts; however, they have the lowest partial score in the important area of viability. Notwithstanding, their high score in the area of sustainability (due to fissile material production) is an important advantage. The fourth score is for the SCWR(T). As in the case of the SCWR(F), they have an average performance in comparison to the other Generation IV reactors, but as a thermal reactor, their performance in the area of sustainability is lower than the performance of assessed fast reactors.

The fifth score is assigned to GFRs. They have an average overall performance as in the case of the previous three reactors, resulting in an outstanding score in the areas of economics and sustainability. The lowest score corresponds to MSRs, which have an average performance in several areas taken into account. Even though they have a high score in the area of sustainability, they currently present the lowest partial score in important areas such as viability of the concept and materials.

(c) International cooperation

Argentina has an extensive background in the development of its scientific and technological capabilities in the field of peaceful uses of nuclear energy. At the regional level, it participates actively in the Regional Co-operation Agreement for the Promotion of Nuclear Science and Technology in Latin America and the Caribbean (ARCAL) and the Latin American Network for Education in Nuclear Technology (LANENT), both in the framework of the activities promoted by the IAEA. It has become a supplier of nuclear technology in Latin America, emphasizing the link with countries such as Brazil, Cuba, Peru and the Bolivarian Republic of Venezuela, and it has also developed expertise in the formation and training of human resources throughout the region by means of its academic institutes.

This trend has allowed Argentina to become a recognized leader in Latin America and an active participant in international organizations and multilateral forums such as the IAEA, the Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, the Nuclear Suppliers Group, the International Framework for Nuclear Energy Cooperation, the Nuclear Security Summit and the Global Initiative to Combat Nuclear Terrorism. Its vocation for the responsible development of nuclear technology and applications, with full respect for the non-proliferation regime and the interest in cooperating with its neighbours, has been reflected in the consolidation of a significant number of intergovernmental and interinstitutional agreements with its respective counterparts far and wide across the region.

3.1.1.5. Conclusions

Argentina has maintained a policy of national development through the training of human resources and R&D of technologies for the peaceful uses of nuclear energy. Socioeconomic ups and downs that the country experienced in the past has at times slowed activities carried out in the field, but the trajectory of local development was never lost. An example of this is the experience gained through the increased participation of local companies in the construction and operation of nuclear power plants. Ultimately, Argentina seeks to reach the capacity to build

[2] Reactor prototype BREST-OD-300 (300 MW(e)), in the Russian Federation 2015–2020; Advanced LFR European Demonstrator (ALFRED, 125 MW(e)), to be built in Romania 2019–2024, among others.

nuclear power plants from foreign designs to augment its productive national capacities to develop all stages of the nuclear fuel cycle.

When the CAREM-25 national design (25 MW(e)) will be constructed and connected to the grid, the country will have consolidated the technology of power reactors, and will open a new stage in which it could scale the prototype into plants with higher capacities, such as CAREM-150 (150 MW(e)). The scenarios presented in Annex VI indicate that between 6620 MW(e) and 10 370 MW(e) of installed nuclear capacity will be required to achieve the objectives in the medium and long term. As the CAREM-150s are projected to cover between 8% and 11% of the capacity required, the difference should initially be covered by external providers.

With regard to the fuel necessary to supply the future nuclear power plants, if the reasonably assured and inferred resources (RAR+IR) are accounted for (<US $130/kg U), a total of 18 531 t U would be available, and that amount is insufficient to cover the requirements through 2050. Since uranium mining was stopped in 1995 for economic reasons, it has been necessary to import uranium concentrate to supply national requirements. Although at present the market conditions for uranium are not a constraint for the reactivation of mining, there is pressure from environmental organizations and civil society against such activity. In order to replace gradually uranium imports with domestic uranium, and in turn to meet the future needs of nuclear fuel for the planned nuclear power plants, it is essential to perform exploration for the discovery of new uranium resources, together with assuring its production.

Although it is considered highly likely that the results of this study are maintained in the medium term, the R&D programmes associated with the Generation IV concepts are currently active, and one of the goals of GIF is to update its Technology Roadmap. As this may occur in the future, there may be changes to these results in light of actual performance from the prototypes and capacity reactors upon operation. From the point of view of international cooperation, the vast experience gained by Argentina over the last 63 years and its consolidation through the national educational institutes, position it as a regional focal point for human resources training.

Finally, once the CAREM-25 and CAREM-150 are constructed, they can be exported, complementing the exports of research and radioisotope production reactors in which the country is currently established internationally.

3.1.2. Assessment of impact of fuel cycle back end options on levelized unit electricity cost of produced electricity based on nuclear fuel cycle in Armenia

3.1.2.1. Introduction

The general objective of the fuel cycle back end Armenian case study under Task 2 of the IAEA SYNERGIES project is to develop different options for management of spent nuclear fuel. An important factor for selecting a strategy for final spent nuclear fuel management is an economic evaluation that allows a comparative analysis of different scenarios of the nuclear fuel cycle and/or reveals the influence of the different components of the nuclear fuel cycle on the entire fuel cycle cost. Finding a solution for spent nuclear fuel may determine the direction of implementation of the national strategy for the further development of nuclear power generation. Due to the amount of accumulated spent fuel and the lack of generally accepted solutions for its optimal final management, a long term assessment is necessary to determine the impact on the cost of electricity produced by nuclear power plants in the various spent fuel scenarios.

Common approaches for assessing the impact of the final stage of the nuclear fuel cycle on the levelized unit energy cost (LUEC) when considering an 'idealized model' are presented in Ref. [3.4]. It is shown that the assessment of the final stage impact of the nuclear fuel cycle requires determining the value of the entire fuel cycle, including the construction costs of nuclear power plants, nuclear fuel procurement, maintenance, storage and disposal of spent nuclear fuel.

This study is performed under the SYNERGIES Task 1, Scenario C.3: Russian Federation, Ukraine and Armenia case study on the water cooled, water moderated power reactor (WWER)–fast reactor collaborative deployment scenarios aimed at solving the problem of accumulating spent fuel inventory to match fast reactor deployment needs. For the reference scenario, an option for long term storage of spent fuel at the nuclear power plant site with no restrictions on spent nuclear fuel accumulation has been considered. For sensitivity analysis, the study considers the options for removal of spent fuel from the nuclear power plant site and export to another country for reprocessing using different transport solutions (road, rail and air). The complete case study can be found in Annex I on the CD-ROM accompanying this publication.

3.1.2.2. Objective and problem formulation

The objectives are the following:

(i) Collection and analysis of baseline information on the current status and projections of the development of nuclear power in Armenia.
(ii) Development of a model for nuclear fuel cycle options, including:
   - Spent fuel storage at the nuclear power plant site;
   - Spent fuel storage at the nuclear power plant site and removal of spent fuel from nuclear power plant site to geological disposal;
   - Export of spent fuel from Armenia using different transport solutions (road, rail and air) for reprocessing and final disposal in another country.
(iii) Assessment of the impact of spent fuel management costs on the cost of electricity produced by nuclear power plants.
(iv) Development of recommendations on optimizing the cost of spent fuel management and sustainable nuclear energy development in Armenia.

3.1.2.3. Assumptions, methods and data used

(a) General assumptions

The Armenian energy system is modelled by generation forms, independent of specific power units and regional features. To cover the growing electricity demand and to provide the contractual obligations with the Islamic Republic of Iran, only the implementation of nuclear technologies can be proposed. It is assumed that the WWER-1000 unit will replace the existing Armenian nuclear power plant in 2026. Starting from 2035, six VBER-300[3] reactors will come into operation for each decade. The last (sixth) VBER-300 will be introduced into the power system in 2095. It is assumed that seven LWRs with uranium oxide (UOX) fuel will be commissioned by 2100.

Armenia has no nuclear fuel cycle industry and uses an open nuclear fuel cycle. The existing WWER-440 nuclear unit operates with a three year fuel cycle. The spent nuclear fuel, before its transfer to the dry storage, is kept for 5 years in the reactor cooling pool.

In 2000, the construction of the first stage of the spent fuel dry storage facility was completed. The construction was performed with Framatome (France). The spent fuel dry storage facility has been put into operation, and the transfer of spent fuel is performed according to the requirements of the license given by the Armenian Nuclear Regulatory Authority. The volume of the first stage of storage is now completely filled with spent fuel.

In 2005, an agreement was signed with AREVA TN International (France) for construction of the additional three stages of the dry storage facility. The financing was allocated from the State budget. The second stage was completed and put into operation in the spring of 2008 and the first part of the spent nuclear fuel has been transferred into dry storage. The third stage of spent fuel dry storage construction is planned to be started in 2015.

In order to perform the mentioned assessment, the discount rate is taken at 10% for all the considered scenarios. The following input data for all scenarios were used.

(b) Data used for the front end of the nuclear fuel cycle

- Uranium resources: Uranium resources are considered to be unlimited during the modelling period. The cost of natural uranium is considered at US $110/kg.
- Conversion and enrichment: Historically, the cost of conversion services varied between US $8–15/kg HM [3.5]. This value is assumed to be US $7.5/kg HM in the model. Uranium conversion stage is considered as a service. The process of uranium enrichment is considered as a service with a cost

[3] VBER-300 is a medium sized PWR being developed by Afrikantov Experimental Design Bureau for Mechanical Engineering (OKBM) (Russian Federation).

per separative work unit (SWU) of US $160 purchased on the world market [3.5]. It is assumed that the global market for uranium enrichment services is not limited. Tails assay is 0.25%.

- Fuel fabrication: Fabrication of fresh fuel for LWRs is considered as service purchased at the price of US $300/kg HM. Average world prices of fuel fabrication for PWRs were US $250/kg HM in 2008 [3.6].
- WWER-440 unit: Real economic data were used for tariffs.

(c) Data used for light water reactors

Three types of LWR are considered in the scenarios: WWER-440, WWER-1000 (Project B-392) and VBER-300. It is planned to commission only one WWER-1000 reactor in 2026. After that, a series of small reactors (VBER-300) are expected to be implemented up to the end of the century. The technical and economic data of considered reactors are presented in Table 3.3 [3.7].

Four different fresh nuclear fuels modification have been modelled in this study. Their parameters are presented in Table 3.4 [3.7].

(d) Data used for the back end of the nuclear fuel cycle

The technical and economic data are presented in Table 3.5.

TABLE 3.3. TECHNICAL AND ECONOMIC PARAMETERS OF THE REACTORS USED IN THE MODEL

Parameter	WWER-440	WWER-1000	VBER-300
Heat capacity (MW)	1375	3000	912
Electric capacity (MW)	375	1060	325
Efficiency (%)	32	35	
Installed capacity utilization factor (%)	72	85	85
Fuel enrichment (%)	3.8	4.3/4.7	5
Av. burnup for fuel assemblies (MW·d/kg)	42.66	48/60	60
First load (t HM)	40.2[a]	68.4/72.8[b]	22.2
Annual reload (t HM)	9.00[a]	20.2/16.1[c]	4.4
Overnight cost (US $/kW)	—	5000	5500
Fixed costs (US $/kW)	50	50	50
Variable costs (US $/MW·h)	1	1	1
Operation lifetime (years)	13[d]	60	60
Construction period (years)	—	6	5
Fuel fabrication (US $/kg)	300	300	300
Construction of spent fuel dry storage (US $/kg)	150	150	150
Cost of disposal of spent nuclear fuel (US $/kg)	600	600	600

[a] The first load: 115.2 kg × 349 pcs = 40 204.8 kg; annual reload: 115.2 kg × 78 pcs = 8985.6 kg.
[b] The first load: (old fuel) 163 pcs × 494 kg × 0.85 = 68 443.7 kg; (new fuel) 163 pcs × 545 kg × 0.85 = 72 844.0 kg.
[c] Annual reload: (old fuel) 36 pcs × 545 kg × 0.85 = 16 088 kg; (new fuel) 48 pcs × 494 kg ×0.85 = 20 155 kg.
[d] From the starting year (2013) to the decommissioning year (2026) of the modelling.

TABLE 3.4. VALUE OF THE NUCLEAR FUEL PARAMETERS USED IN THE MODEL

Parameter	WWER-440	WWER-1000 (new)	WWER-1000 (old)	VBER-300
Av. enrichment (%)	3.82	4.7	4.28	5
Burnup (MW·d/kg)	42.66	60.0	48.0	60.0
Weight of UO_2 in fuel assemblies (kg)	115.2	545	494	n.a.[a]
Number of assemblies in the reactor (pcs)	349	163	163	n.a.[a]
Fuel assemblies annual load (pcs)	78	36	42	n.a.[a]

[a] n.a.: not applicable.

TABLE 3.5. VALUE OF PARAMETERS USED IN THE MODEL (US $/kg HM)

Parameter	Value
Transport by	
Road	112.5
Rail	50
Air	500
Cost of spent fuel dry storage construction [3.8–3.11]	150
Cost of the geological disposal of spent fuel [3.8–3.12]	600
Cost of the processing without the return of processing waste [3.13]	2000

3.1.2.4. Summary presentation and analysis of the results

(a) Summary presentation

Three scenarios of spent nuclear fuel management options considered in the study are presented in Table 3.6. The results of economic analyses of nuclear fuel scenarios according to Table 3.6 are summarized below.

(b) Analysis of the results: Management of spent fuel without construction of small reactors

(i) Construction of the spent fuel dry storage at the nuclear power plant site

This scenario assumes that the existing WWER-440 reactor will produce electricity until 2026. After decommissioning of the existing unit, a new WWER-1000 type reactor will be introduced into the national grid for electricity generation from 2026 to 2086. A total of 3148 spent nuclear fuel assemblies will be accumulated from WWER-440, which amounts to 362.649 t. Spent fuel from the WWER-440 will be removed after five years of storage in the reactor cooling pond.

The total accumulation of spent nuclear fuel assemblies from the WWER-1000 will be 1022.036 t (16.088 t × 59 years + 72.844 t). Fuel assemblies will be unloaded after 12 years of storage in the reactor cooling pool. The first group of fuel assemblies will be unloaded from cooling ponds in 2039, and the last one in 2099. By 2100, 1 384.685 t of spent fuel will be accumulated from the WWER-440 and WWER-1000 nuclear units. Figure 3.3 shows the accumulation of spent fuel over the planning period.

LUEC for the specified scenario is estimated at US $53.69/MW·h, and its structure is presented in Table 3.7.

TABLE 3.6. SPENT NUCLEAR FUEL MANAGEMENT CONFIGURATION OPTIONS

Configuration	Option	Comment
Management of SNF without construction of small reactors	Construction of SFDS at the NPP site (Reference Scenario) Construction of SFDS at the NPP site and export of SNF from the NPP site to another country by rail for reprocessing and disposal of SNF after 50 years of storage at the NPP site	WWER-440 Fuel enrichment 3.82% Burnup 42.66 MW·d/t SNF of WWER-440 is located in SFDS after the interim cooling in the cooling pool (5 years) WWER-1000 Fuel enrichment 4.7% Burnup 60 MW·d/kg SNF of WWER-1000 will be located in SFDS after the interim cooling in the cooling pool (12 years) Operation time of SFDS is unlimited Volume of SFDS is limited by numbers of SNF assemblies of WWER-1000 and WWER-440
	Construction of SFDS at the NPP site and transfer SNF to geological disposal after 50 years of SNF storage at the NPP site	
Export of SNF from the NPP site to another country by different types transport for reprocessing and final disposal, old fuel modification, construction of small reactors	Export by road Export by rail Export by air	WWER-1000 Fuel enrichment 4.28% Burnup 48 MW·d/kg Removal after the interim storage of SNF in the cooling pool (5 years) and 50 years of storage in SFDS Return of radioactive waste is not considered Removal rate of SNF corresponds to the annual loading of the reactor(s) (or to the total annual load of the reactors) Construction of small reactors is envisaged
Export of SNF from the NPP site to another country by different types transport for reprocessing and final disposal, new fuel modification, construction of small reactors	Export by road Export by rail Export by air	WWER-1000 Fuel enrichment 4.7% Burnup 60 MW·d/kg Removal after the interim storage of SNF in the cooling pool (12 years) and 50 years of storage in SFDS Return of radioactive waste is not considered Removal rate of SNF corresponds to the annual loading of the reactor(s) (or to the total annual load of the reactors) Construction of small reactors is envisaged

Note: NPP — nuclear power plant; SFDS — spent fuel dry storage; SNF — spent nuclear fuel; WWER — water cooled, water moderated power reactor.

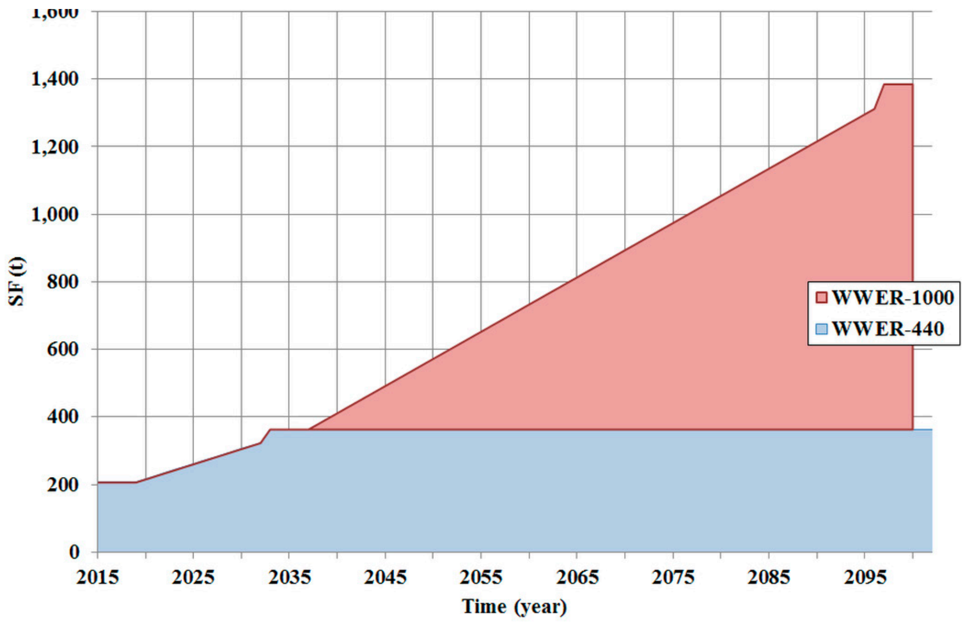

FIG. 3.3. Accumulation of spent fuel over the planning period.

TABLE 3.7. STRUCTURE OF THE LEVELIZED UNIT ENERGY COST

Cost component	US \$/MW·h
Investment cost	35.25
Fixed cost	9.25
Variable cost	0.81
Uranium cost	3.02
Conversion cost	0.21
Enrichment cost	3.22
Fabrication coat	1.71
Spent fuel management cost	0.23
Levelized unit energy cost	53.69

(ii) Construction of the spent fuel dry storage and export of the spent fuel from the nuclear power plant site to another country

This scenario considers construction of spent fuel dry storage and subsequent export of spent fuel by railway transport. In this scenario, spent fuel export starts after its 50 years placement in dry storage. Figure 3.4 shows the dynamics of accumulation and removal of WWER-440 spent fuel from storage. It is assumed that 205.632 t of spent fuel accumulated before 2013 will be exported by 2063 (i.e. 50 years later). If the spent fuel is removed at a rate of 8.9856 t/year (an annual load of WWER-440), then the start of spent fuel removal produced until 2013 should be scheduled up to 2051.

Spent nuclear fuel from the WWER-440 — which will be transferred to spent fuel dry storage after 2013 — will begin to be exported in 2063 and will be completely removed by 2086 (see Fig. 3.4). The blue relates to the spent fuel from the WWER-440, which had accumulated before 2013; the brown is associated with spent fuel from the WWER-440, which will be produced after 2013. In total, 362.65 t of spent fuel will be produced.

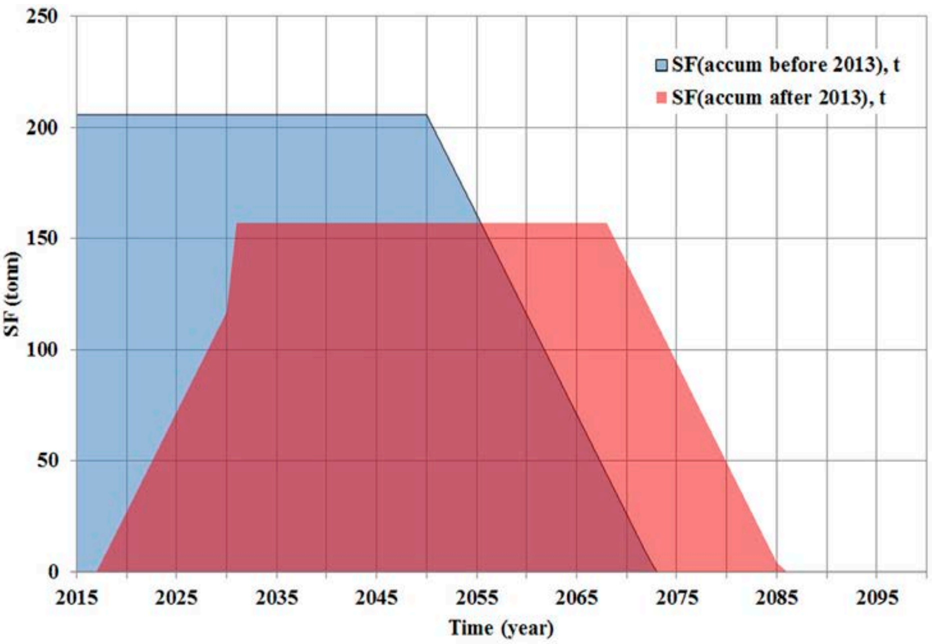

FIG 3.4. Removal of WWER-440 spent fuel from spent fuel dry storage.

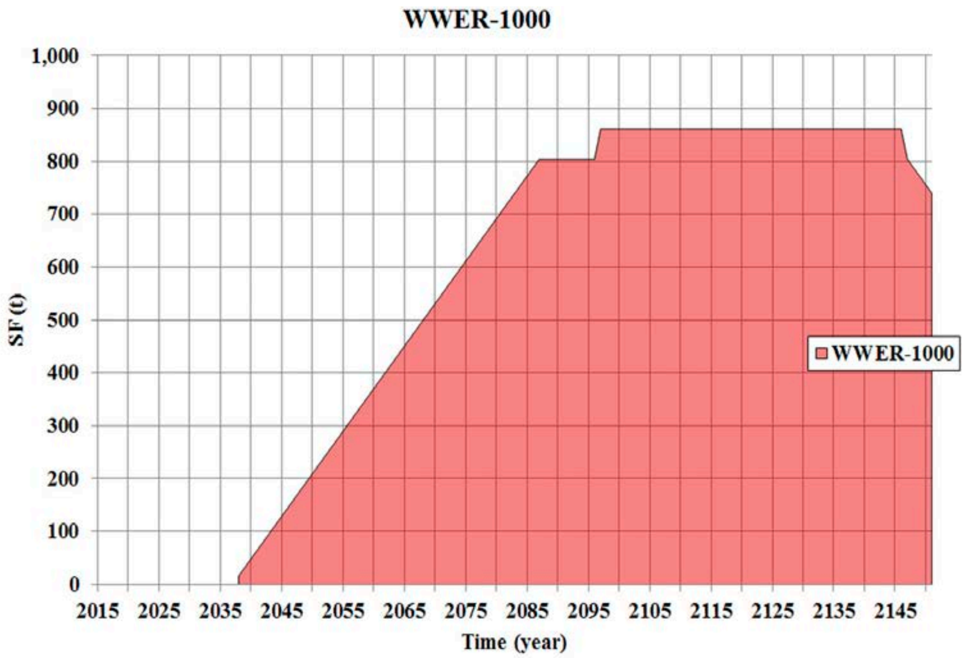

FIG. 3.5. Change of volume of WWER-1000 spent fuel in spent fuel dry storage.

The dynamics of accumulation and removal of spent fuel from the WWER-1000 are shown in Fig. 3.5. In consideration of the removal, 850 t of spent fuel will accumulated. Removal of spent fuel from the WWER-1000 will begin in 2089 (2027 + 12 + 50 years) and will be completed by 2152. Annual removal of spent fuel is limited by the amount of annual loading/unloading of WWER-1000 fuel, which is 16.088 t/year. The export of spent fuel from the WWER-1000 is shown in Fig. 3.6 In total, the WWER-1000 will produce 1022.036 t of spent fuel.

The LUEC for the specified scenario is estimated at US $53.82/MW h, and its structure is presented in Table 3.8.

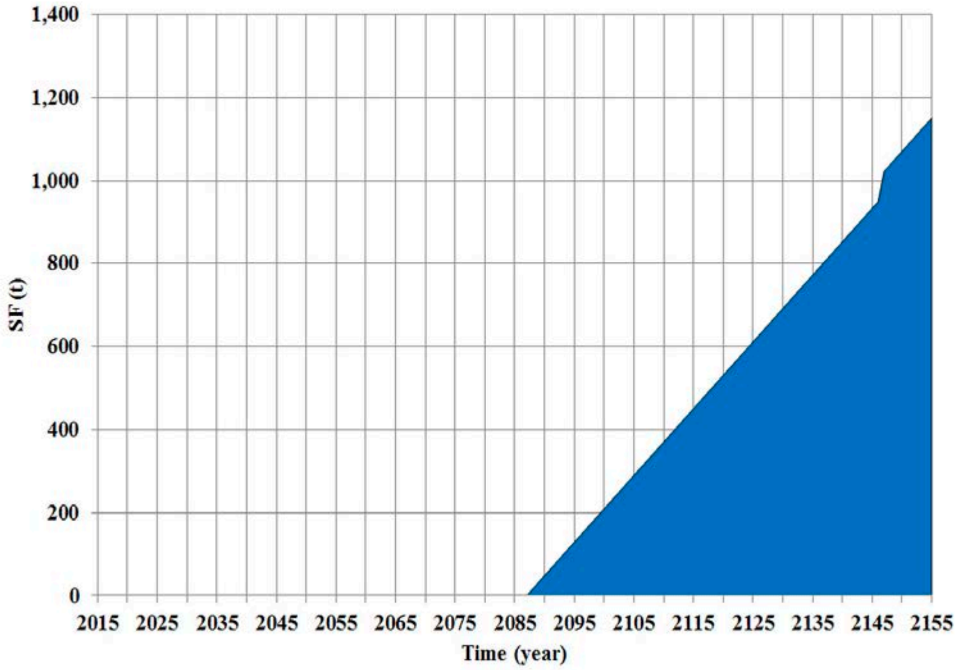

FIG. 3.6. Export dynamics of WWER-1000 spent fuel from spent fuel dry storage.

TABLE 3.8. STRUCTURE OF THE LEVELIZED UNIT ENERGY COST

Cost component	US $/MW·h
Investment cost	35.25
Fixed cost	9.25
Variable cost	0.81
Uranium cost	3.02
Conversion cost	0.21
Enrichment cost	3.22
Fabrication cost	1.71
Spent fuel management cost	0.23
Transfer cost	0.003 1
Cost of the processing without the return of processing waste	0.12
Levelized unit energy cost	53.82

(iii) Construction of the spent fuel dry storage and transfer of spent fuel to geological disposal

This scenario considers the construction of spent fuel dry storage from the WWER-440 and WWER-1000, as well as the construction of a geological repository for disposal of spent fuel. It is assumed that the spent fuel will initially be in spent fuel dry storage. After 50 years, the spent fuel will be transferred to a geological disposal. The dynamics of the accumulation of WWER-440 spent fuel in centralized storage and the dynamics of spent fuel replacement into a geological repository are shown in Fig. 3.4. Accumulation of WWER-1000 spent fuel, and

TABLE 3.9. STRUCTURE OF THE LEVELIZED UNIT ENERGY COST

Cost component	US $/MW·h
Investment cost	35.25
Fixed cost	9.25
Variable cost	0.81
Uranium cost	3.02
Conversion cost	0.21
Enrichment cost	3.22
Fabrication cost	1.71
Spent fuel management cost	0.23
Disposal cost	0.04
Levelized unit energy cost	53.73

its removal and placement in a geological repository are shown in Figs 3.5 and 3.6. The LUEC for the specified scenario is estimated at US $53.73/MW·h, and its structure is presented in Table 3.9.

(c) Analysis of the results: Construction of small reactors, export of spent fuel from the nuclear power plant site to another country (old fuel modification)

This scenario considers the connection to the grid of WWER-1000 in 2026, as well as construction of a series of small VBER-300 reactors in 2035, 2045, 2055, 2065, 2075 and in 2095. The scenario considers the operation of the WWER-1000 reactor with fuel enrichment of 4.28% (old fuel modification). The structure of installed nuclear capacity and electricity generation until 2100 is shown in Figs 3.7 and 3.8. Total installed capacity in 2080 will increase to 2625 MW (1000 MW — WWER-1000 and 1625 MW — 5 × VBER-300).

Amounts of spent fuel are shown in Figs 3.9 and 3.10. Approximately 2376 t of spent fuel will be produced up to 2100. In total, there will be 1592 t of spent fuel in spent fuel dry storage collected from all the reactors considering the export of spent fuel (see Fig. 3.11). The spent fuel export rates from dry storage are taken at the level of annual loads for both WWER-440 and WWER-1000 reactors and the rate of export for small reactors is considered equal to spent fuel supply rate. Spent fuel exports for WWER-440 and WWER-1000 are limited by the number of annual loads for the corresponding reactors. The export of spent fuel from VBER-300 is determined by the volume of spent fuel unloaded from all reactors in a given year.

The export costs can be summarized as follows:

(i) Export by road: The cost of transporting spent fuel by road is set at US $112.5/kg HM. The LUEC will be US $57.157/MW·h (see Table 3.10).
(ii) Export by rail: The cost of transporting spent fuel by rail is set at US $50/t HM. The LUEC will be US $57.153/MW·h (see Table 3.11).
(iii) Export by air: The cost of transporting spent fuel by air is set at US $500/kg HM. The LUEC will be US $57.18/MW·h (see Table 3.12).

(d) Analysis of the results: Construction of small reactors, export of spent fuel from the nuclear power plant site to another country (new fuel modification)

This scenario considers the implementation of a WWER-1000 reactor and a series of small VBER-300 reactors. Operation of the WWER-1000 reactor is modelled with fuel enrichment to 4.7%. Figures 3.7 and 3.8 show the structure of installed capacities and electricity generation, respectively. All reactors until 2100 will produce

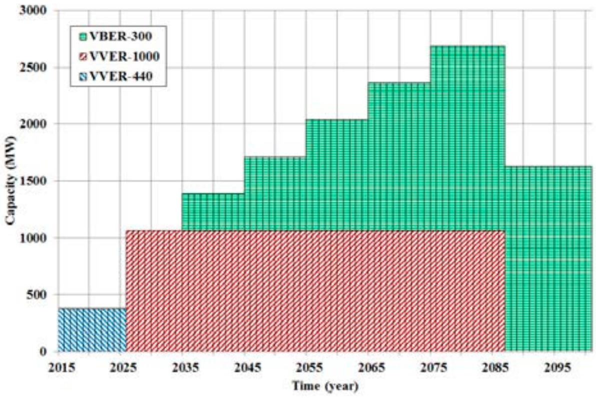

FIG. 3.7. Installed capacities of nuclear units.

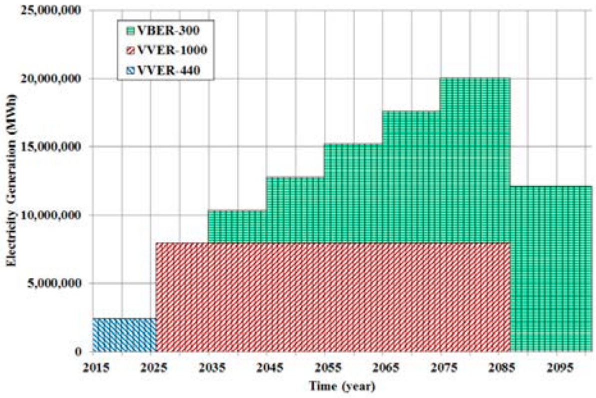

FIG. 3.8. Structure of electricity generation by nuclear units.

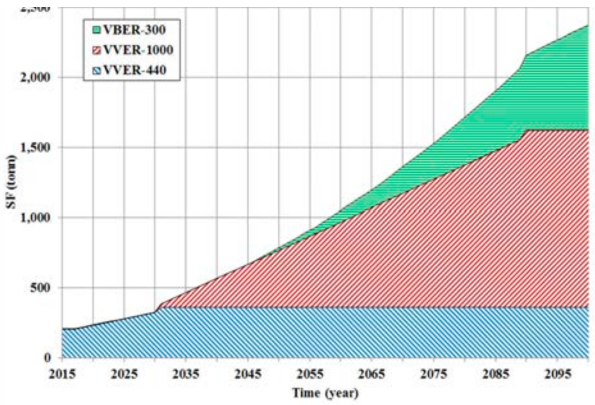

FIG. 3.9. Amount of spent fuel without export (total).

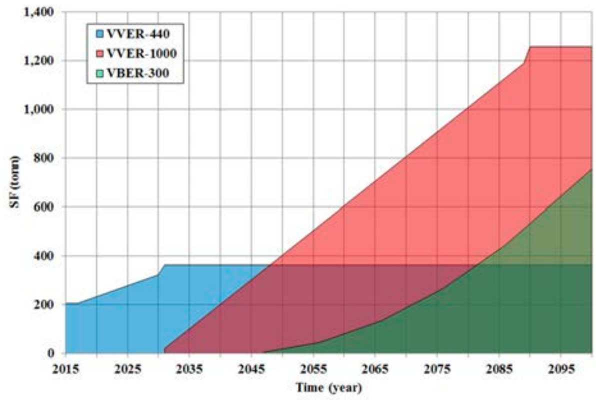

FIG. 3.10. Amount of spent fuel without export (by reactor type).

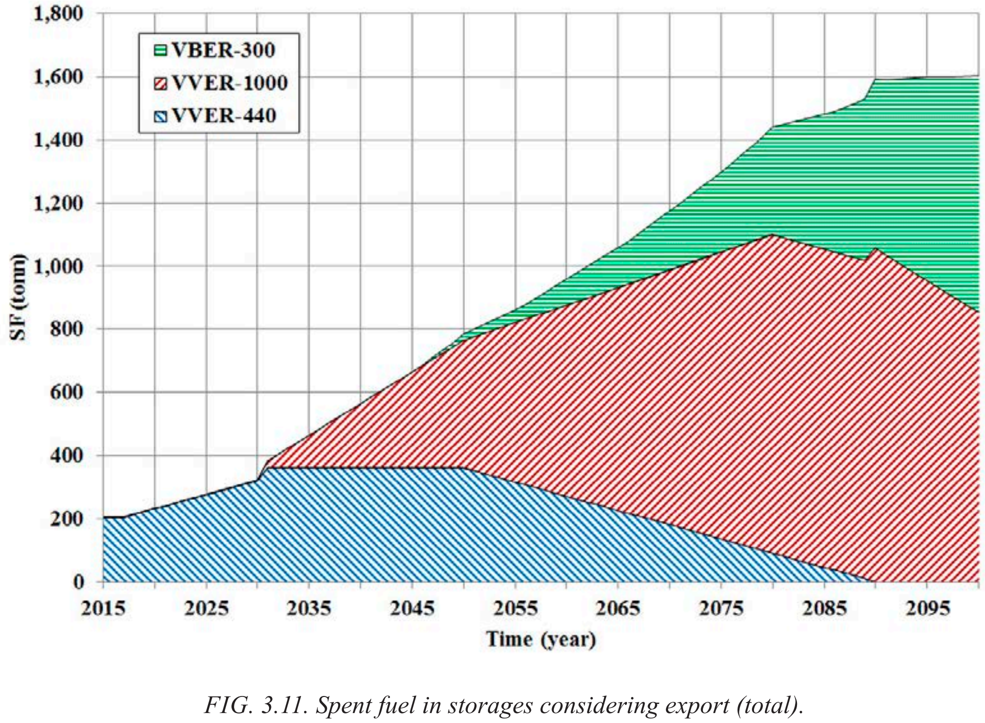

FIG. 3.11. Spent fuel in storages considering export (total).

TABLE 3.10. ROAD: STRUCTURE OF THE LEVELIZED UNIT ENERGY COST

Cost component	US $/MW·h
Investment cost	38.73
Fixed cost	8.98
Variable cost	0.83
Uranium cost	3.07
Conversion cost	0.21
Enrichment cost	3.24
Fabrication cost	1.67
Spent fuel management cost	0.29
Transfer cost	0.007 2
Cost of the processing without the return of processing waste	0.13
Levelized unit energy cost	57.157

TABLE 3.11. RAIL: STRUCTURE OF THE LEVELIZED UNIT ENERGY COST

Cost component	US $/MW·h
Investment cost	38.73
Fixed cost	8.98
Variable cost	0.83
Uranium cost	3.07
Conversion cost	0.21
Enrichment cost	3.24
Fabrication cost	1.67
Spent fuel management cost	0.29
Transfer cost	0.003 2
Cost of the processing without the return of processing waste	0.13
Levelized unit energy cost	57.153

2140 t HM of spent fuel (see Fig. 3.12). Accumulation of spent fuel into the storage for the period up to 2100 is shown in Fig. 3.13 (with export). The export costs can be summarized as follows:

(i) Export by road: The LUEC will be US $56.896/MW·h (see Table 3.13).
(ii) Export by rail: The LUEC will be US $56.893/MW·h (see Table 3.14).
(iii) Export by air: The LUEC will be US $56.92/MW·h (see Table 3.15).

TABLE 3.12. AIR: STRUCTURE OF THE LEVELIZED UNIT ENERGY COST

Cost component	US $/MW h
Investment cost	38.73
Fixed cost	8.98
Variable cost	0.83
Uranium cost	3.07
Conversion cost	0.21
Enrichment cost	3.24
Fabrication cost	1.67
Spent fuel management cost	0.29
Transfer cost	0.032 2
Cost of the processing without the return of processing waste	0.13
Levelized unit energy cost	57.18

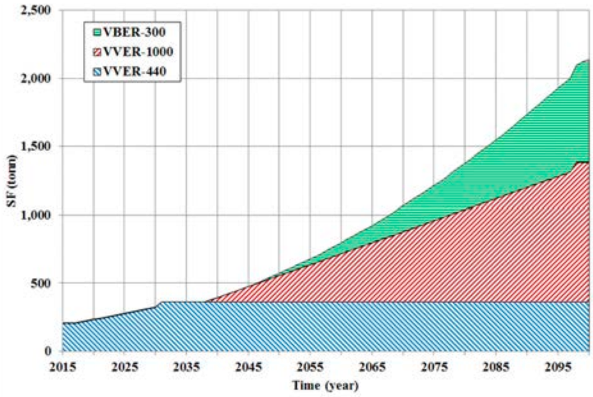

FIG. 3.12. Total amount of spent fuel (excluding export).

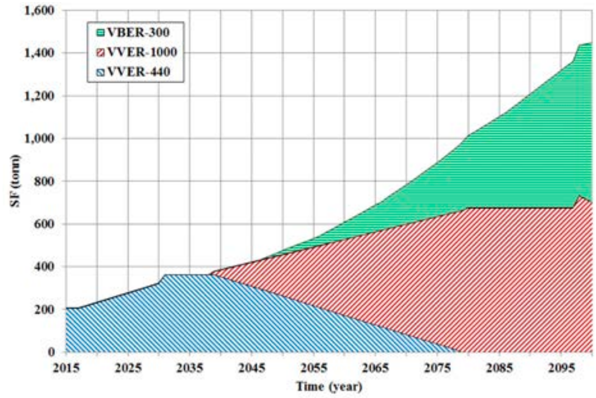

FIG. 3.13. Total accumulation of spent fuel in storage (with export).

3.1.2.5. Conclusions

The low sensitivity of the LUEC to the modification of the scenario conditions relates to the following factors (see Table 3.16):

— Small contribution of the final stage of nuclear fuel cycle in the overall structure of the present value;
— Small exported amounts of spent fuel in the period under review;
— Extended period of spent fuel removal (until 2150);
— Postponement of spent fuel for the later export or disposal;
— Lack of the consideration of SFD operational costs and geological storage in the model.

In the structure of the LUEC, the share corresponding to the final stage of the nuclear fuel cycle represents a small part (4%). Changes in the price of spent fuel management have an insignificant effect on changes in the present value of electricity. The option with the construction of spent fuel dry storage at the base conditions is an acceptable solution to the management of spent fuel. However, given the need of spent fuel management after the project period in spent fuel dry storage, export of spent nuclear fuel may be more attractive after its discharge from the reactors cooling pool.

TABLE 3.13. ROAD: STRUCTURE OF THE LEVELIZED UNIT ENERGY COST

Cost component	US $/MW·h
Investment cost	38.73
Fixed cost	8.98
Variable cost	0.83
Uranium cost	3.00
Conversion cost	0.20
Enrichment cost	3.21
Fabrication cost	1.60
Spent fuel management cost	0.21
Transfer cost	0.006 2
Cost of the processing without the return of processing waste	0.11
Levelized unit energy cost	56.896

TABLE 3.14. RAIL: STRUCTURE OF THE LEVELIZED UNIT ENERGY COST

Cost component	US $/MW·h
Investment cost	38.73
Fixed cost	8.98
Variable cost	0.83
Uranium cost	3.00
Conversion cost	0.20
Enrichment cost	3.21
Fabrication cost	1.60
Spent fuel management cost	0.21
Transfer cost	0.002 7
Cost of the processing without the return of processing waste	0.11
Levelized unit energy cost	56.893

TABLE 3.15. AIR: STRUCTURE OF THE LEVELIZED UNIT ENERGY COST

Cost component	US $/MW h
Investment cost	38.73
Fixed cost	8.98
Variable cost	0.83
Uranium cost	3.00
Conversion cost	0.20
Enrichment cost	3.21
Fabrication cost	1.60
Spent fuel management cost	0.21
Transfer cost	0.027 4
Cost of the processing without the return of processing waste	0.11
Levelized unit energy cost	56.92

TABLE 3.16. THE LEVELIZED UNIT ENERGY COST IN DIFFERENT SCENARIOS

Scenario	US $/MW·h
Management of SNF without construction of small reactors	
SFDS	53.69
SNF export by rail	53.82
SNF transfer to geological disposal	53.73
Construction of small reactors, export of SNF from the NPP site to another country (old fuel modification)	
SNF export by rail	57.153
SNF export by road	57.157
SNF export by air	57.18
Construction of small reactors, export of SNF from the NPP site to another country (new fuel modification)	
SNF export by rail	56.893
SNF export by road	56.896
SNF export by air	56.92

Note: NPP — nuclear power plant; SFDS — spent fuel dry storage; SNF — spent nuclear fuel.

3.1.3. Economic value of uranium recovered from LWR spent fuel as fuel for HWRs

3.1.3.1. Introduction

The reprocessing of spent nuclear fuel from LWRs to extract plutonium with which to create a mixed oxide (MOX) fuel, typically depleted uranium mixed with plutonium, meets two important objectives of SYNERGIES: it increases the sustainability of the global fuel cycle by generating more energy per mined uranium mass, and it increases proliferation resistance, since the quality of the plutonium in the overall fuel cycle decreases. However, previous work has shown that reprocessing is difficult to justify on the basis of economics alone [3.14].

Heavy water reactors (HWRs) have a low parasitic neutron capture rate such that natural uranium can be used as fuel. The creation of ^{239}Pu from neutron capture on ^{238}U capture is very efficient, permitting a very high fissile utilization, which is the energy yield per initial mass of fissile material (the same as the burnup divided by the initial fissile mass fraction in the fuel). The fissile utilization increases with enrichment and reaches a peak at an optimized value of around 1.2wt% ^{235}U/uranium [3.15]. The reprocessed (or recycled/recovered) uranium from LWR spent nuclear fuel, a by-product of the MOX fuel cycle, typically has a fissile content of 0.76–0.92wt% ^{235}U/uranium and can therefore be used very efficiently in an HWR.

Reuse of reprocessed uranium in HWRs is a potential near term collaborative architecture which increases the proliferation resistance and sustainability of the fuel in the global NES. This work attempts to establish the economic case for such an architecture (or strategy). If a net economic benefit can be demonstrated, then the share of this benefit which accrues to the holder of the reprocessed uranium increases the economic motivation for MOX reprocessing. In this way, the benefits to the global NES would be improved substantially by this synergy. This study falls within the framework of Task 1 on the evaluation of synergistic collaborative scenarios towards sustainable NESs — nuclear fuel cycle synergies. The complete case study can be found in Annex III on the CD-ROM accompanying this publication.

3.1.3.2. Objective and problem formulation

Currently, reprocessed uranium is considered a waste product without significant value. The reasons for this assessment are the following:

- Few reactor types can use it directly because its enrichment is too low.
- It contains sufficient residual radioactivity to contaminate process lines (i.e. in plants for uranium enrichment).
- The isotopic composition specifications of reprocessed uranium are variable, depending on its origin, so that more effort is required to qualify its use in fresh fuel.

Returning reprocessed uranium to the NES fuel cycle would help to increase global sustainability. The objective of this study is to explore the economics of burning reprocessed uranium and demonstrate that a synergy between an reprocessed uranium generator and user could be made mutually beneficial from this point of view.

The economic value of reprocessed uranium to a user is defined to be the cost of fuel which would otherwise have to be obtained to produce the same total energy. This cost defines the theoretical maximum that a user of reprocessed uranium should be willing to pay for it, and a synergy would be a situation when a user was paying less than this maximum (thus saving on fuel costs) while the reprocessed uranium producer was making a profit on a MOX reprocessing line by-product. For convenience, and because there is a large supply of this material, the focus has been placed on analysing the use of reprocessed uranium extracted from spent nuclear fuel from an LWR having approximately a burnup of 33 MW·d/kg. The uranium isotopic composition from this fuel, originally 3.25wt% ^{235}U/uranium, is defined as [3.14]:

- ^{235}U: 0.924 2wt%;
- ^{236}U: 0.408 8wt%;
- ^{238}U: 98.667 0wt%.

The question to be answered is how does the value compare to other potential uses of the reprocessed uranium (i.e. recycling into an LWR of similar type, or use to support minor actinide disposal). The economic value of reprocessed uranium to an HWR will be assessed by its exit burnup relative to the exit burnup of natural uranium (the fuel which would otherwise be used). Higher exit burnup (assuming constant power) reduces the total fuel required (and hence the fuelling expense) in inverse proportion.

3.1.3.3. Assumptions, methods and data used

(a) Assumptions

The assumptions include the following:

(1) There is an active market (a balance between supply and demand) in reprocessed uranium. This ensures that the price obtainable for reprocessed uranium by the sellers is set closely by its economic value to buyers. It is assumed that natural uranium is part of this market.
(2) HWRs can be reconfigured easily to use reprocessed or natural uranium in different core loads, depending on availability and price, and switching fuels requires no other cost. However, long term fuel contracts are more likely. The economic analyses would be similar for such contracts, so these two assumptions are not strictly required.
(3) Shipping of reprocessed uranium from LWRs to HWRs via the reprocessing and fuel refabrication facility has a negligible relative cost.
(4) Reprocessed uranium is already available as a by-product of MOX production with no further costs. These extra costs, if included, would reduce its value, and would have to be considered in a more complete study.
(5) The HWR is assumed to run in an 'advanced fuel cycle mode' using a 43 element fuel bundle, and smaller numbers of fuel bundles per shift (e.g. a 2 bundle fuel shift with reprocessed uranium based fuels instead of an 8 bundle fuel shift with natural uranium fuel), and fewer core reactivity devices for adjusting reactivity and flux distributions. In this mode, the exit burnup is defined as that burnup for which the core losses in reactivity (due to neutron leakage and parasitic absorption) are 3–4% (0.1% = 0.001 dk/k = 1 mk = 100 pcm) depending on the fissile content of the reprocessed uranium. For comparison, when natural uraniumis used as fuel, reactivity devices such as liquid zone controllers and adjusters filled with light water serve the purpose of flattening the flux axially, and core reactivity losses due to neutron leakage are approximately about 4.5% (45 mk = 4500 pcm).
(6) The central pin of the advanced fuel cycle bundle is assumed to be poisoned (containing a burnable neutron absorber) to achieve the same coolant void reactivity or slightly less than that of natural uranium (so that safety analyses do not have to be updated).

(b) Codes

The lattice physics code WIMS-AECL 3.1.2.3 [3.16] was used to determine the expected exit burnup of the reprocessed uranium. A burnup weighting of k_{inf} during a full burnup calculation gives an estimate of the k_{inf} of an infinite lattice core with a distribution of such bundles from fuel changes. When this k_{inf} is less than 1 + leakage + parasitic absorption (see assumption 5), the exit burnup has been reached.

(c) Input data

The burnup of natural uranium in an HWR is assumed to be 7500 MW·d/t (7.5 MW·d/kg). The fuel/coolant/moderator temperatures and densities are similar to that of a CANDU-6 pressure tube heavy water reactor.

3.1.3.4. Summary presentation and analysis of the results

(a) Overall economic value of reprocessed uranium

The economic values of reprocessed uranium for direct recycling in an HWR and for re-enrichment (for use in an LWR) are shown in Fig. 3.14.

Since fuel bundles made of reprocessed uranium, or re-enriched reprocessed uranium, displace normal fuel bundles, in each case the cost of natural uranium and the cost of fuel bundle assembly hardware are parameters which affect its value. Estimates of US \$105.26/kg and US \$250/kg have been made for HWR and LWR hardware, respectively [3.14]. Reference [3.14] assumes an extra US \$10/kg for the handling of the (slightly radioactive) reprocessed uranium fuel instead of natural uranium, this expense has been added to the cost of HWR fuel hardware for reprocessed uranium as well.

At the current (nominal) natural uranium cost of US \$90/kg, it can be seen that reprocessed uranium from 33 MW·d/kg used nuclear fuel is worth about US \$230/kg if recycled in an HWR, while US \$100/kg if re-enriched for an LWR. Thus, a synergetic collaboration with an HWR is more attractive (to a MOX reprocessor) than with an LWR. The absolute value of the difference becomes larger as the price of natural uranium rises to US \$300 (probably a natural ceiling, since at this price it starts to become economical to mine sea water [3.17]).

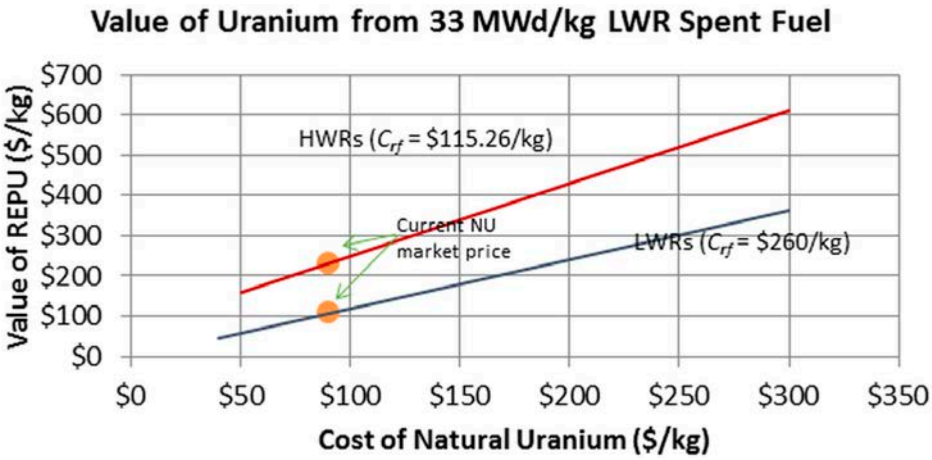

FIG. 3.14. Value of reprocessed uranium as a function of the cost of natural uranium, with fabrication costs held fixed.

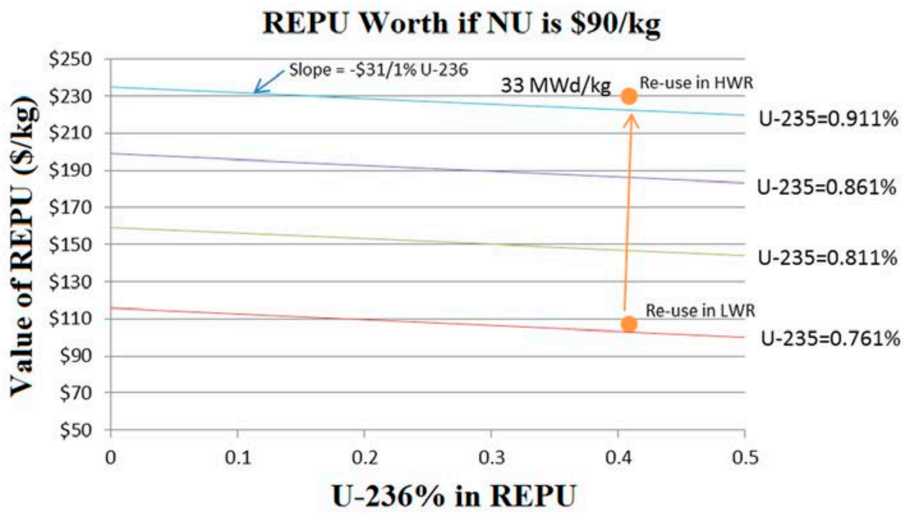

FIG. 3.15. Reduction in the value of reprocessed uranium as a function of the presence of ^{236}U.

(b) Effect of ^{236}U

Reprocessed uranium naturally contains ^{236}U from neutron capture, without fission, on ^{235}U. No primordial ^{236}U exists in natural uranium due to its relatively short half-life of 2×10^7 years. The effect of ^{236}U was investigated for the actual amount present in the nominal 33 MW·d/kg used nuclear fuel or 0.408 8wt%, and parametrically as a sensitivity case, and the results are shown in Fig. 3.15. Independent of the amount of ^{235}U, the effect of ^{236}U is seen to decrease the value of reprocessed uranium by around US $3 for every 0.1wt% increase. For 33 MW·d/kg used nuclear fuel, the reprocessed uranium value is reduced by about US $12/kg. Uranium-236 is more of a problem in LWRs because it is a better absorber in the somewhat harder neutron spectrum there. It is estimated in Annex III that ^{236}U reduces the worth of reprocessed uranium to be used for re-enrichment by about twice this amount to about US $24/kg.[4]

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[4] This assumes centrifuge type re-enrichment, where a significant amount of ^{236}U is carried along with the ^{235}U. Laser enrichment techniques would presumably reduce the cost of ^{236}U in reprocessed uranium to nearly US $0 for LWRs.

(c) Coolant void activity

Because the coolant provides little moderation in a CANDU-6 pressure tube heavy water reactor, loss of coolant tends to result in a net positive reactivity insertion. The effects of this coolant void reactivity (CVR) insertion are considerably mitigated by the very long neutron lifetime in HWRs, about ten times that of a PWR. It can be seen that the positive effect of ^{236}U on the (core averaged) CVR is greater than the negative effect of increasing enrichment. It is assumed that the reactor will be returned to a standard CVR (for fuel with ^{235}U = 0.711wt% and ^{236}U = 0wt%). In the case of reprocessed uranium with 0.924 2wt% $^{235}U/U$ and 0.402 2wt% $^{236}U/U$, the effect is 0.13 mk. Increasing the neutron poison in the central element to reduce the CVR by this amount adds a burnup penalty worth approximately US $3.70/kg.

3.1.3.5. Conclusions

It is estimated that aqueous reprocessing of LWR fuel will cost US $1000–2000 per kg [3.11]), so the recovery of uranium with an enrichment near that of natural uranium (currently at ~US $90/kg) cannot be the main economic driver. However, low burnup reprocessed uranium supplied to an HWR in place of natural uranium has the potential to save the utility up to US $230/kg in fuelling costs (given current prices for natural uranium and HWR fuel bundle fabrication). Divided up between the reprocessor and HWR, this potential profit makes the reprocessing case more economically feasible, and therefore moves the world towards a more sustainable fuel cycle. The profit in other scenarios, such as re-enrichment of the reprocessed uranium for use in LWRs, or mixing the reprocessed uranium with depleted uranium to make a natural uranium equivalent fuel for HWRs (discussed in the full case study in Annex III on the CD-ROM accompanying this publication), result in an reprocessed uranium value much more closely tied to the price of natural uranium and are therefore less attractive as economic drivers.

Reprocessed uranium contains the neutron absorbing poison ^{236}U. When re-enriched, the reactivity loss due to this poison has to be compensated by over-enriching the fuel slightly. It was estimated that this over-enrichment reduces the worth of the reprocessed uranium by about US $24/kg ^{236}U. The burnup penalty imposed by ^{236}U is less in an HWR, resulting in a value of US $12/kg ^{236}U, but the effect of ^{236}U on HWR CVR requires additional poisoning in the central pin which subtracts an additional US $4/kg from the reprocessed uranium value.

3.1.4. A reactor synergy: Using HWRs to transmute Am from LWR spent fuel

3.1.4.1. Introduction

The synergy between LWRs and HWRs has the potential to improve the sustainability of nuclear power by improving the characteristics of high level waste (HLW) from LWR spent nuclear fuel. This case study was undertaken as part of Task 3, on options for minor actinide management. The complete case study can be found in the Annex XXVII on the CD-ROM accompanying this publication. It was focused on quantification of the theoretically well known high potential of HWRs to act as effective burners/transmuters of minor actinides and, in particular, of americium isotopes [3.18–3.22], as well as on analysis of economic benefits may result from such a burning. The physics behind this stems from the fact that fission cross-sections of americium isotopes in a specific neutron spectrum of a HWR are extremely large, so that the burning process in a HWR could compete with that in a fast reactor where the neutron flux is high while the cross-sections are low.

3.1.4.2. Objective and problem formulation

The objective was to analyse the synergy between LWR and HWR organized as follows [3.19]: LWR spent fuel is chemically reprocessed to produce fresh americium based fuel for an HWR; as this fuel alone is not sufficient for the HWR to operate, reprocessed uranium based fuel is also produced when reprocessing LWR spent fuel; both these types of fuel are loaded in a regular HWR to enable its operation. In this, the following assumptions were made:

— The operator already practises single recycle of MOX fuel in LWR, such fuel being produced from reprocessed spent fuel of the reactors of the same type.

— The new investments related to the synergy analysed would therefore be needed only to extract and transport the americium.
— In this, the operator may incur some losses related to a reduction of the amount of potential reprocessed uranium fuel available.

Economic advantages were examined that the LWR operator could acquire from reducing the volume and nomenclature of HLW for final disposal and the conditions under which such advantages could be gained. A material flow analysis was also conducted to compare the proposed synergy to a non-synergistic case where the americium in LWR spent fuel is not separated from the HLW stream. From the perspective of the HWR operator, a comparison of the radiation characteristics of fresh and used fuel is conducted to determine how this synergy affects the handling of HWR fuel and the long term disposal of HWR spent fuel. From the perspective of the LWR operator, a comparison of the decay power of HLW is conducted to determine how this synergy affects the long term disposal of HLW.

3.1.4.3. Assumptions, methods, codes and input data used

The following assumptions were made for the proposed synergy:

— The LWR operator has already decided to reprocess the spent fuel using the plutonium and uranium recovery by extraction (PUREX) process, and recycle the plutonium as MOX fuel for LWRs.
— Standard design of HWR core can with no modifications accommodate the new type of fuel (i.e. reprocessed uranium + americium).

WIMS-AECL v.3.1.2.1 code with an ENDF/B-VII based library of neutron cross-sections was used for fuel burnup calculations in the HWR. The following assumptions were made for the economic analysis of the proposed synergy:

— The value of reprocessed uranium to the LWR operator is based on its re-enrichment for use as LWR fuel.
— The net economic benefit of this synergy to Utility H would be positive (the averted fuel costs outweigh increased fuel handling and disposal costs).
— The discharge burnup of LWR spent fuel is 27.35, 33, 43, 47 or 53 GW·d/t.
— The LWR spent fuel has been stored for either 5 or 30 years after discharge.

The economics of the proposed synergy were analysed using a break-even analysis based on Ref. [3.14], with the data from Ref. [3.9]. The following assumptions were made for the material flow analysis of the proposed synergy:

— The scenario starts in 2000 and ends in 2110.
— The global nuclear electricity demand is assumed to be the moderate case from the GAINS report.
— In 2010, 346 and 48 legacy LWRs and HWRs, respectively, were operating, and begin retiring in 2030 at a constant rate such that all legacy reactors are retired by 2060.
— The ratio of LWRs to HWRs is always approximately 12 to ensure that all americium is burned in the synergy scenario.
— Reprocessed uranium that is not recycled into HWRs is stored indefinitely.
— LWR parameters:
  • Nominal electrical power is 1 GW(e);
  • Thermal efficiency is 33%;
  • Load factor is 85%;
  • Reactor lifetime is 40 years;
  • UOX fuel is 4.1% ^{235}U, for a discharge burnup of 47 GW(th)·d/t;
  • MOX fuel is 90% depleted uranium and 10% plutonium, for a discharge burnup of 51 GW(th)·d/t.
— HWR parameters:
  • Nominal electrical power is 0.6 GW(e);

- Thermal efficiency is 33%;
- Load factor is 85%;
- Reactor lifetime is 30 years;
- Fuel is either natural uranium or reprocessed uranium + americium, for a discharge burnup of 7.5 GW(th)·d/t.

— Fuel cycle parameters:
- Enrichment tails is 0.3%;
- Reprocessing of LWR spent fuel begins in 2030;
- Reprocessing losses is 0.1%.

The material flow analysis was conducted using the VISION fuel cycle simulator.

3.1.4.4. Summary presentation and analysis of the results

(a) Economic analysis

The economic analysis was performed under the assumptions outlined in Section 3.1.4.2. In this, the analysed functional was cost saving on final disposal resulting from americium burning in HWR within the synergistic case considered, also taking into account economic penalties owing to more complex fuel cycle organization and reductions in reprocessed uranium amount potentially usable in reactors. The criterium was that the cost saving should be larger than all economic penalties, and the specific objective of studies was to understand which parameters and in which way may affect the functional meeting of this criterium.

Figure 3.16 shows the minimum required cost savings for final disposal of HLW to make the synergy economically viable. In this figure, the space above the shown curves (for two different storage times) corresponds to the area of economic viability of the considered synergy, while below these curves lies the area where such a synergy would result in economic losses to the operator of LWRs.

The main observations are that the longer the storage time for the LWR spent fuel before reprocessing, the larger the savings in the final disposal of HLW would be needed to make the considered synergy economically viable (additional saving of US $ 30/kg HLW for the additional 25 years of storage). Contrary to this, the increase of ^{235}U content in LWR spent fuel would result in a reduction of the necessary savings in final disposal of HLW, owing to lower amount of reprocessed uranium that would be needed to support americium burning in HWR.

The study performed also included sensitivity analysis to clarify the impact of different parameters of relevance — americium separation cost, content of uranium in reprocessed uranium, enrichment and fuel fabrication cost for reprocessed uranium, and fuel fabrication cost for natural uranium — upon the conclusions

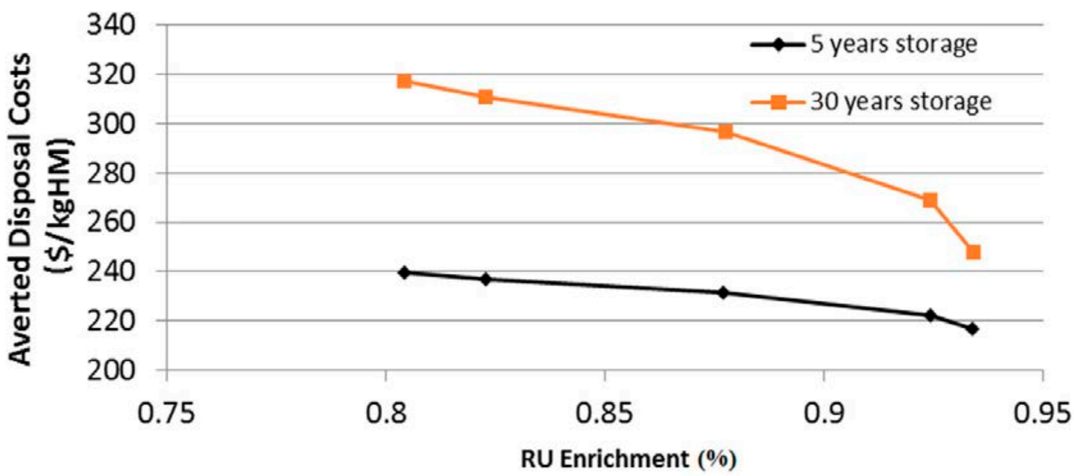


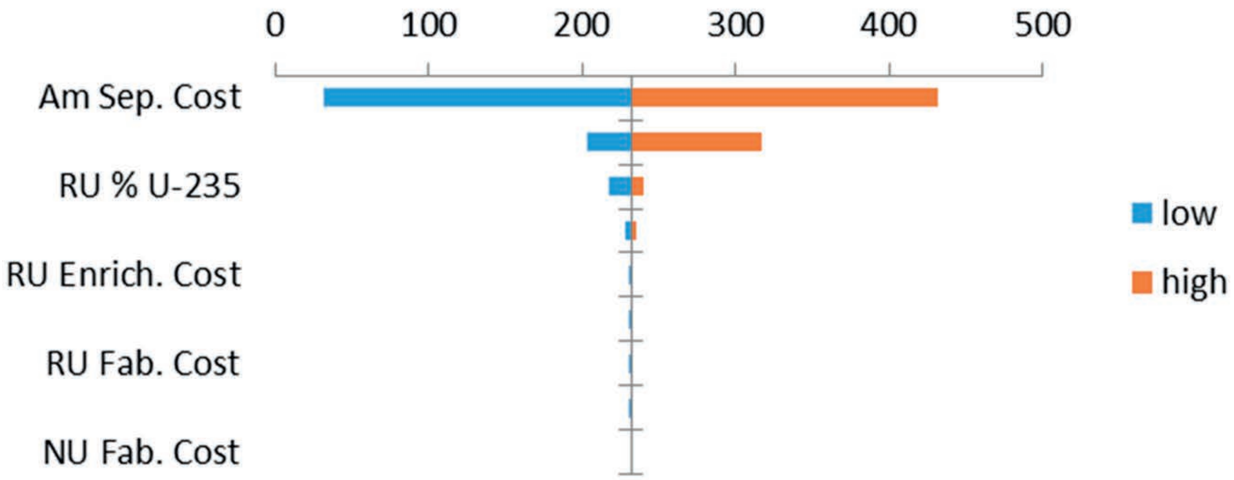
FIG. 3.16. Minimum cost savings in final disposal of high level waste to make the synergy economically viable for each storage duration and reprocessed uranium enrichment.

derived. The results are given in Fig. 3.17, in the form of 'tornado' graphs. Independent variations of each parameter were applied from its minimum to maximum value. It was found that of all the parameters considered it is the cost of americium separation in reprocessing that has the strongest (and really significant) impact on the conclusion (i.e. minimum cost savings in HLW disposal needed to make the synergy economically viable).

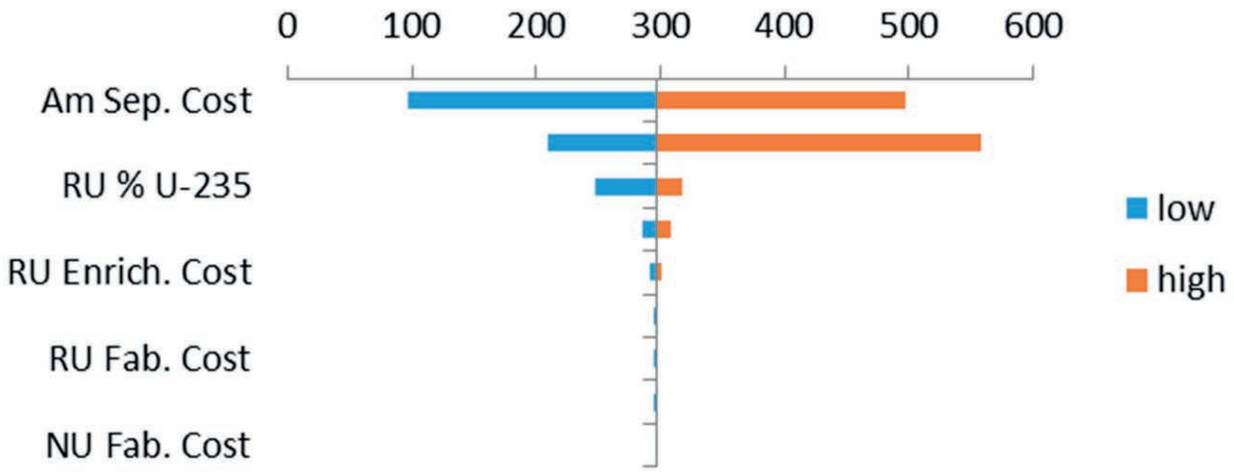
Apart from Fig. 3.17, there is another parameter the variation of which strongly affects the conclusion — the natural uranium cost [3.19]. An increase in natural uranium cost from US \$20/kg to US \$300/kg would change the savings in HLW disposal (necessary to compensate for economic penalties associated with the considered synergy) from US \$200–210/kg HM to US \$320–560/kg HM.

Figure 3.18 shows the correspondence between the savings in HLW disposal and the cost of americium separation (the latter being the parameter that most affects the former) for different natural uranium costs.

Figure 3.19 presents the ratio of LWR to HWR numbers corresponding to the cases when all fuel (^{241}Am and reprocessed uranium) is transmuted/burned. Since the support ratio for transmuting americium is higher than for burning reprocessed uranium, not all of it produced by LWRs will be required to transmute all of the americium.

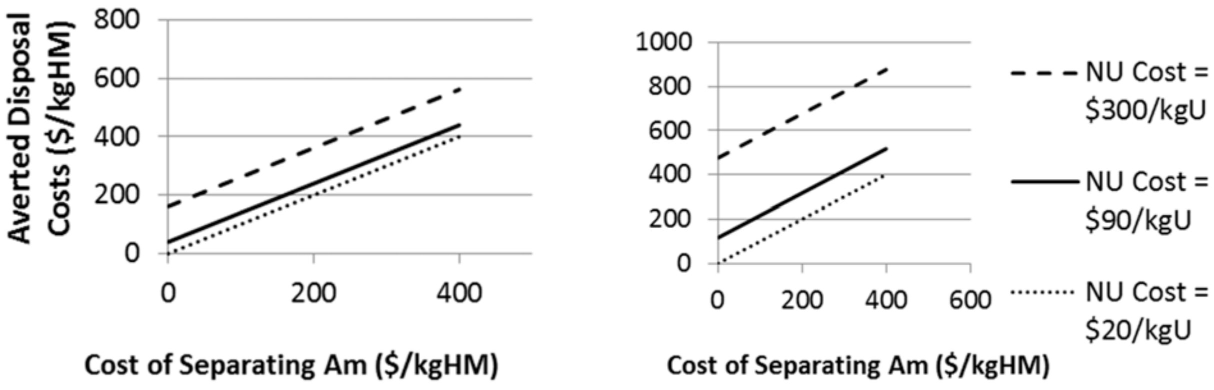


(a) 5 years



(b) 30 years

FIG. 3.17. Minimum savings in disposal costs for the minimum and maximum of each parameter, and each storage duration.



(a) 5 years (b) 30 years

FIG. 3.18. Minimum savings in disposal cost versus the cost of separating americium from the high level waste for each storage duration, and for the minimum, reference value and maximum cost of natural uranium (all other parameters are set to their reference values).

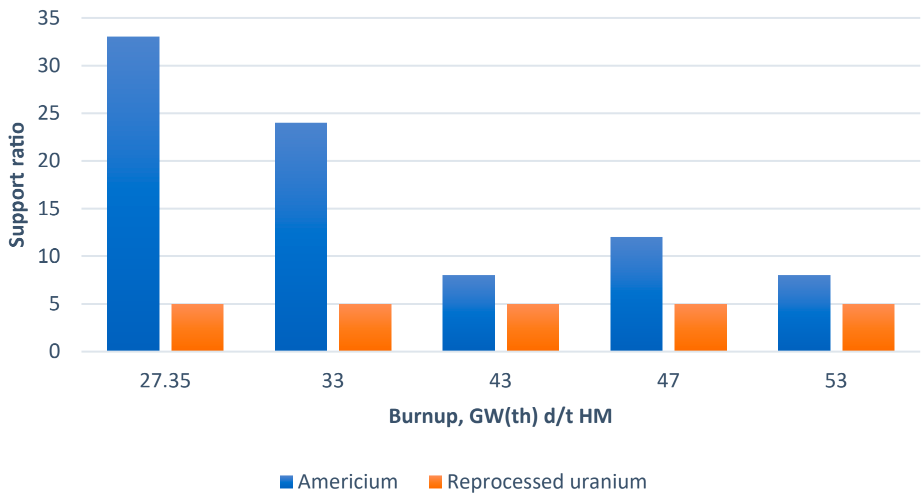


FIG. 3.19. Americium and reprocessed uranium support ratios for each fuel burnup.

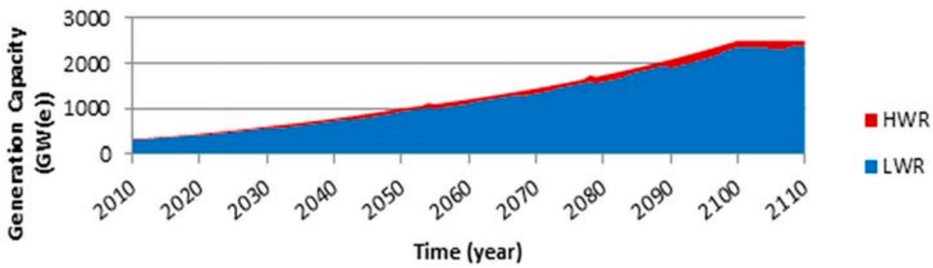
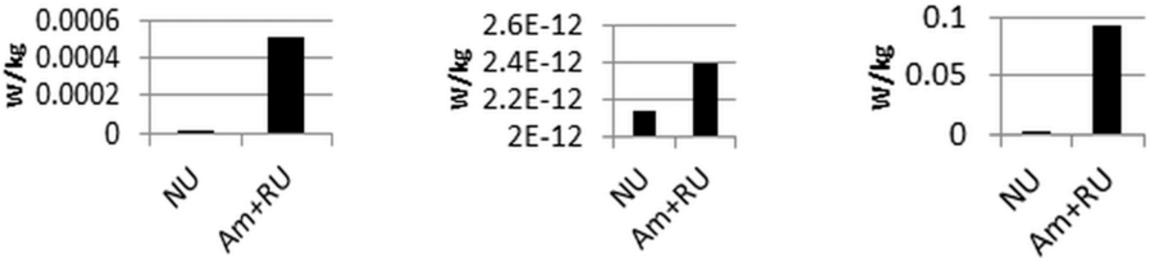


FIG. 3.20. The electricity generation capacity for each reactor type over the duration of the scenarios.

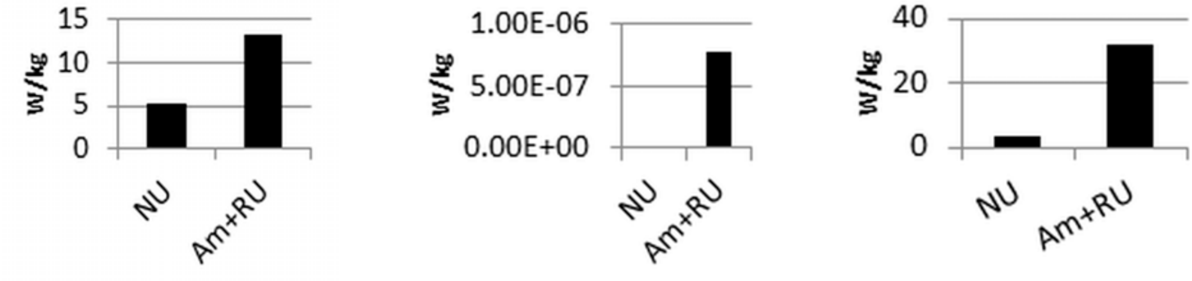
(b) Material flow analysis

The results of synergy and non-synergy scenarios are analysed to quantify the benefit of the synergy to Utility L with respect to HLW. The effects of this synergy on the characteristics of fresh and irradiated HWR fuel are also analysed. Figure 3.20 shows the electricity generation capacity for HWRs and LWRs in both scenarios.



(a) Gamma emissions (b) Neutron emissions (c) Decay power

FIG. 3.21. Fresh heavy water reactor fuel characteristics at discharge.



(a) Gamma emissions (b) Neutron emissions (c) Decay power

FIG. 3.22. Irradiated heavy water reactor fuel characteristics at discharge.

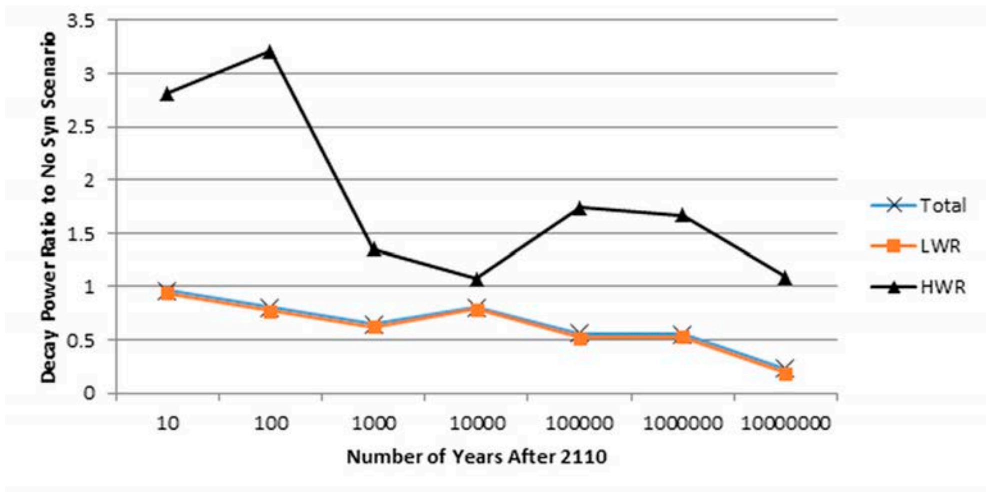


FIG. 3.23. Ratio of the decay power of all irradiated fuel and high level waste in the synergy scenario to the non-synergy scenario.

If Utility H accepts reprocessed uranium and americium from Utility L, then it needs to be ensured that the fresh and irradiated fuel handling facilities for HWRs are capable of handling fuel with increased gamma and neutron emissions, and decay power (W/kg), as is shown in Figs 3.21 and 3.22.

The principal benefit of synergy to Utility L is in the reduction of the long term decay power of its HLW. The ratios of decay power of the reprocessed uranium + americium synergy scenario to the non-synergy scenario at various times are shown in Fig. 3.23.

At 1000 years after the end of the scenario, the decay power of HLW from LWRs in the reprocessed uranium + americium synergy scenario is 0.63 times the decay power in the non-synergy scenario. The synergy scenario for HWRs, on the other hand, produces irradiated fuel with increased long term decay power, which is 1.08–3.2 times as much as the non-synergy scenario. The higher decay power of irradiated HWR fuel in the synergy scenario is due to the reprocessed uranium + americium spent fuel. Over the first 1000 years after discharge, this higher decay power is due to the larger amount of curium and americium in reprocessed uranium + americium spent fuel. The decay power of reprocessed uranium + americium spent fuel does not decrease as quickly as that of natural uranium between 10 and 100 years, and 10 000 and 100 000 years owing to the larger amount of ^{238}Pu in the reprocessed uranium + americium spent fuel at discharge. Overall, the synergy scenario would reduce the long term decay power of irradiated fuel at 1000 years and beyond.

3.1.4.5. Conclusions

This study focused on a proposed synergy between LWRs and HWRs with a potential to improve the sustainability of nuclear power by improving the characteristics of HLW from LWR spent nuclear fuel. Cases were considered where americium from LWR spent fuel is used as new fuel for HWR, amended as necessary by some amount of reprocessed uranium fuel also produced from LWR spent fuel.

(a) Economic analysis

To asess economic viability (attractiveness) of the considered synergy, a parametric study was performed to reveal conditions under which the operator's savings in the cost of HLW final disposal would outweigh the economic penalties associated with a more complex nuclear fuel cycle involving americium separation and transport and with a loss of some of reprocessed uranium with market value as fuel for new HWRs. The attractiveness was shown easier to achieve for shorter storage times of LWR spent fuel before reprocessing and for higher content of ^{235}U in LWR spent fuel. It was also found that the lower are the prices for natural uranium, the lower savings in HLW final disposal would make the considered synergy economically attractive to LWR operators.

(b) Fuel cycle system simulation analysis

A fuel cycle system simulation analysis of the proposed synergy shows that the decay power of HLW for Utility L would be 0.63 times the non-synergy case at 1000 years after the scenario when compared to a non-synergy case. Beyond 100 000 years, this decay power for the synergy is less than 0.6 times the non-synergy case. Utility H would have to cope with fresh fuel that has irradiated fuel with higher gamma and neutron emissions. Utility H would also have to cope with irradiated fuel with long term decay power that is 1.08–3.2 times the non-synergy case. Globally, this synergy would significantly reduce the decay heat of HLW, enabling a more efficient utilization of space in the long term storage facility and thus improving the sustainability of the NES.

3.1.5. 'EU27 scenario' with the extended use of regional fuel cycle centre composed of the La Hague and MELOX facilities

3.1.5.1. Introduction

The EU27 NES scenarios present a diverse, technology mature and rather constant nuclear reactor park already exposed to a growing used fuel inventory starting to saturate available (pool) interim storage capacities [3.23]. The study considers a set of synergies based on the Scenario family A. This study falls within the framework of Task 1, evaluation of synergistic collaborative scenarios towards sustainable NESs and nuclear fuel cycle synergies. The complete case study can be found in Annex IV on the CD-ROM accompanying this publication.

3.1.5.2. Objective and problem formulation

The objective of the study is to analyse four different NES scenarios for the EU27 such that the whole set of these scenarios provides an overview of the impacts different nuclear reactor parks would induce and allowing for interpolation/interpretation of the results for other NES futures as they would realize over time. In each of the four scenarios, the analysis starts from today's installed NES in EU27 essentially composed of LWRs and gradually introducing new LWRs. Two nuclear energy demand scenarios are considered: a low and a high nuclear energy demand reflecting assumptions taken by other authoritative energy market analysis studies.

3.1.5.3. Assumptions, methods, codes and input data used

(a) Scenario LWR + EPR[5] once through cycle

This first scenario assumes the gradual shutdown of the existing LWRs in the EU27 assuming an average 50 year technical lifetime of these nuclear power plants. Gradually, new generation LWRs, in this case assumed EPR like LWRs, are introduced to match the nuclear energy demand.

While not reality today, both the existing reactor park and the new EPRs are assumed in this scenario to operate in a once through fuel cycle mode. The purpose of this scenario, despite other practices already in place in the EU27, is to provide an upper envelope of spent fuel arising and thus transuranic inventory in the fuel cycle and disposed waste. In addition, various countries in the EU27 and maybe as well in the future do use the once through cycle mode for current LWRs owing to a variety of reasons covering economic and societal motivations.

(b) Scenario LWR + EPR UOX/MOX

While not pretending to mimic exactly today's partial recycle of separated plutonium by use of MOX in existing LWRs, this scenario shows the use of partially MOX fuel loaded LWRs and EPRs assuming the reprocessing of all spent fuel discharged from LWRs and EPRs and the recycle of the separated plutonium in MOX in part of the installed nuclear power plants (or via a partial MOX load in all nuclear power plants).

Once again, this scenario is not identical to today's situation but extends the strategy of MOX use to a full use of plutonium mono-recycling in the EU27 NESs, indicating the change in fissile material inventories and waste arising.

3.1.5.4. Summary presentation and analysis of the results

(a) Scenario LWR + EPR once through cycle

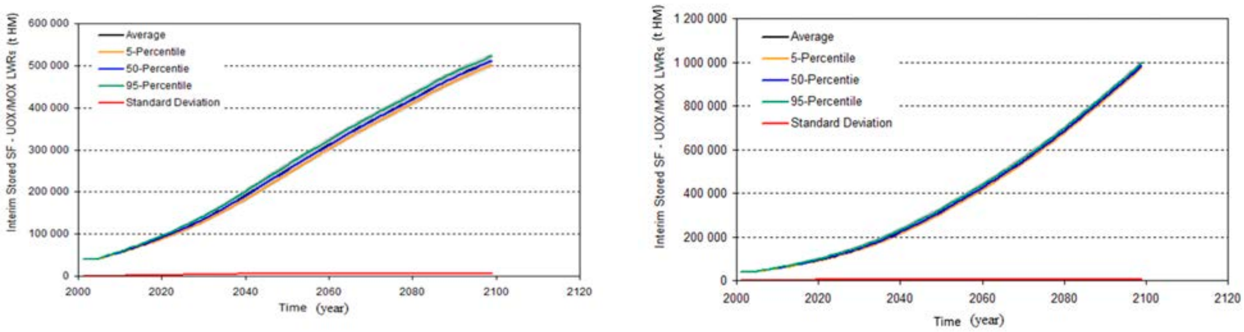
The amount of disposed LWR + EPR fuel is shown in Fig. 3.24 (for low and high nuclear energy demand scenarios) as a distribution based on the distributions assumed for the input variables (i.e. specifically the burnup and cooling time of the LWR = EPR fuels). Both figures show the rather small variation of the disposed spent fuel for the burnup and interim cooling times assumed for the LWR = EPR UOX fuels.

The amount of transuranic in-pile and out-of-pile (and out-of-repository) is shown in Figs 3.25 and 3.26, respectively, for low and high nuclear energy demand scenarios. As the park composition gradually becomes essentially EPR like LWRs dominated and given the rather narrow range of burnup values assumed for the UOX fuel burnups, the distribution of transuranic in-pile remains rather narrow.

Comparable narrow distributions are shown for the cumulative usage of natural uranium (i.e. amount of natural uranium used by scenario from 2005 until the end of century) and the annual enrichment needs, shown in Figs 3.27 and 3.28, respectively, for the low and high nuclear energy demand scenarios.

The relative straightforward relation between the input variables burnup and cooling time for the UOX fuels and the output variables considered in this analysis is clear from the previous figures. No additional detailed analysis of sensitivity analysis was therefore undertaken given the limited conclusions this may entail. A more comparative analysis of all scenarios including this first scenario is provided in the conclusions of this publication.

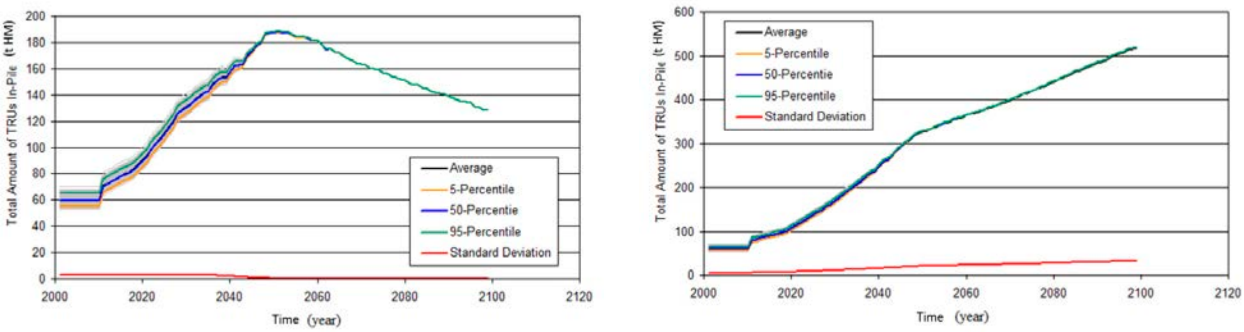
[5] The use of EPR (European pressurized water reactor) does not impose or consider that only EPRs would be built in the European Union. It is more a representation of Generation III LWRs being introduced, replacing the former Generation II LWRs.



(a) Low demand

(b) High demand

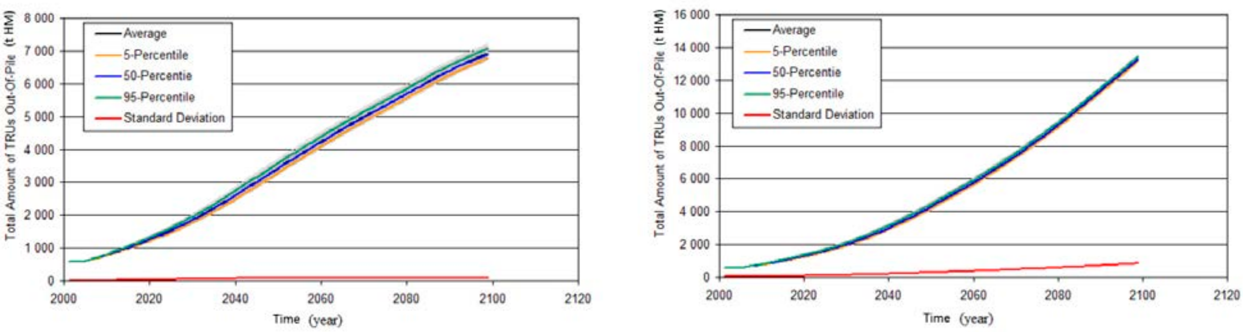
FIG. 3.24. Distribution of disposed LWR+EPR spent fuel.



(a) Low demand

(b) High demand

FIG. 3.25. Transuranic in-pile distribution.



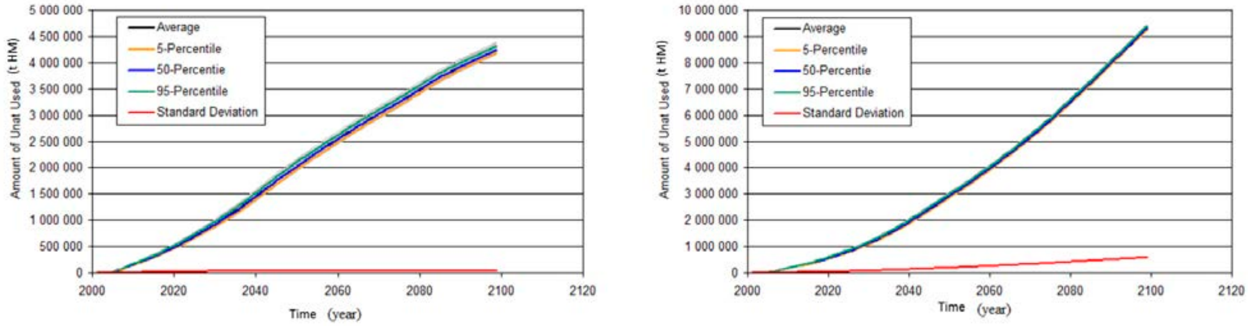
(a) Low demand

(b) High demand

FIG. 3.26. Transuranic out-of-pile distribution.

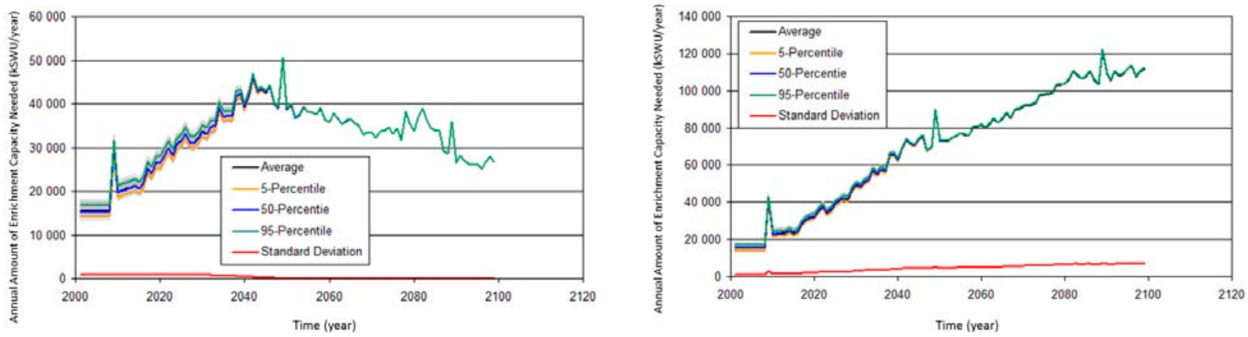
(b) Scenario LWR + EPR UOX/MOX

A comparable sensitivity/uncertainty analysis was undertaken for this scenario, although only for the high nuclear energy demand scenario. The distribution of the amount of spent fuel is shown in Fig. 3.29 as a result of the various burnup and interim cooling times assumed for the UOX and MOX fuels discharged from the LWR and EPRs. The much wider distribution in interim and disposed spent fuel clearly is due to the differences in burnups and cooling times assumed. The outliers of this distribution (i.e. beyond about the 90th percentile) do include cases where the nuclear energy demand cannot be met owing to too long cooling times and thus reduced separated plutonium availability to feed the MOX fabrication plants and thus allowing to load fresh MOX fuel in the EPRs.



(a) Low demand (b) High demand

FIG. 3.27. Cumulative natural uranium used.



(a) Low demand (b) High demand

FIG. 3.28. Annual enrichment needs.

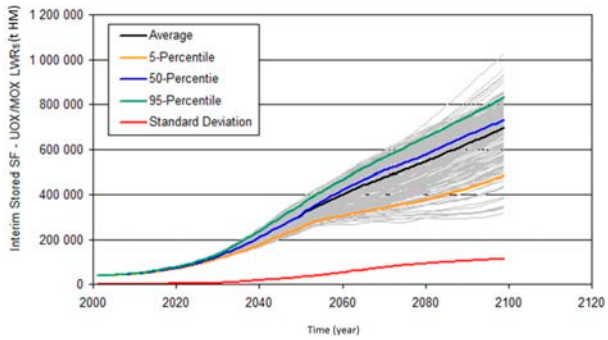


FIG. 3.29. Interim stored spent fuel (high demand).

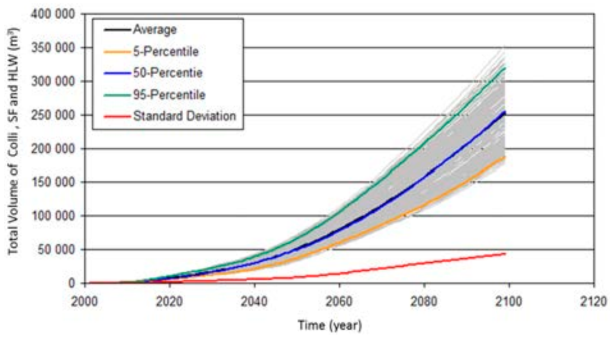


FIG. 3.30. Volume of disposed waste (high demand).

The total volume of disposed waste is shown in Fig. 3.30. Volumes are assumed here in order to show the difference between the estimated volumes of waste given the difference in spent fuel versus HLW packing that may be envisaged for spent fuel and HLWs depending on the type of fuel being disposed of or waste arising from the reprocessing of these fuels.

The total amount of transuranic in-pile and out-of-pile are shown in Figs 3.31 and 3.32, respectively. Again, the wider distribution due to the differences in working inventory versus in-pile amount of transuranics due to differences in burnups and interim cooling times are obvious. The lower than about 10th percentile cases result in a shortage of nuclear energy supply on account of the too long interim cooling times and thus reduction of separated plutonium available for MOX fabrication and thus loading in the EPRs. Obviously, though not considered in the scenario analysis in this case study, this could be circumvented by reducing the fraction of MOX loaded EPRs as well.

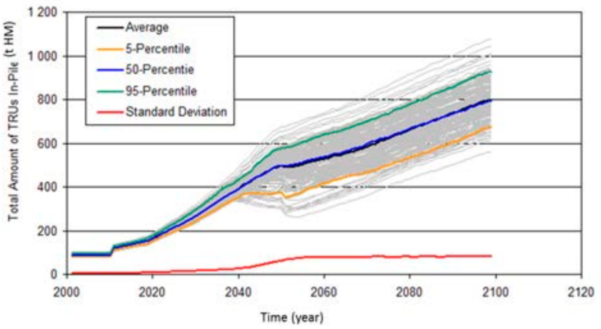


FIG. 3.31. Transuranic in-pile amounts (high demand).

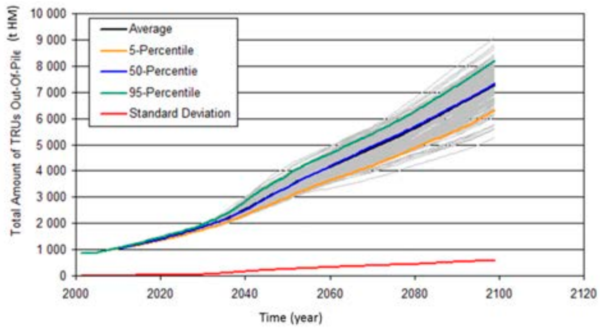


FIG. 3.32. Transuranic out-of-pile (and out-of-repository) amounts (high demand).

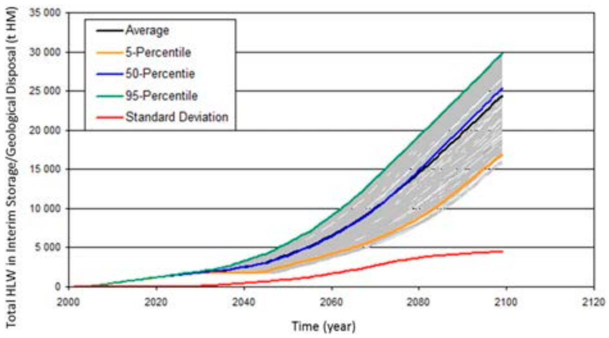


FIG. 3.33. High level waste amounts (high demand).

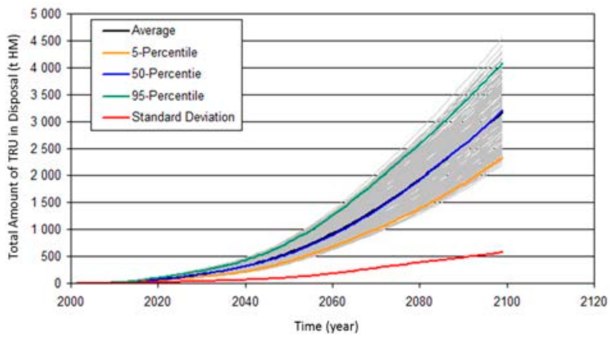


FIG. 3.34. Total amounts of transuranic in disposal (high demand).

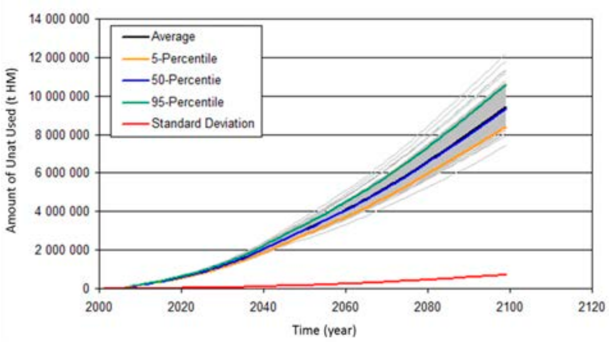


FIG. 3.35. Cumulative natural uranium used (high demand).

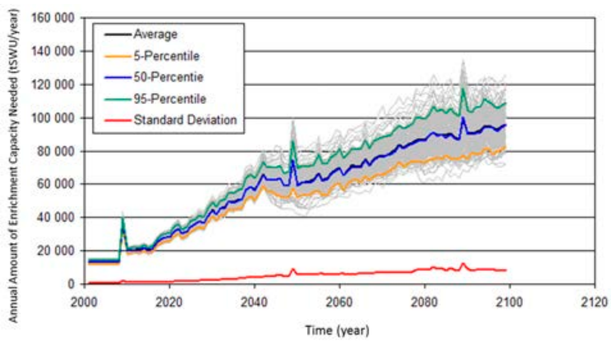


FIG. 3.36. Annual enrichment needs (high demand).

The impact on amount of HLW arising from the reprocessing of the discharged UOX from LWRs and EPRs is shown in Fig. 3.33. Especially the cooling time has a high importance here as any long cooling time results in a late reprocessing and thus delayed arising of HLWs, as can be seen from Fig. 3.33. The total amount of transuranics in disposal — in the disposed MOX fuel and in the HLW (as from Fig. 3.33) — are shown in Fig. 3.34.

The cumulative amount of natural uranium used by this scenario as function of the sampled burnups is shown in Fig. 3.35. Here, the cooling time does not have a direct impact, as this amount of natural uranium is only based on the fresh fuel demand for the evolving reactor park. However, if the cooling time becomes too long, and thus the requested nuclear energy demand may not be met, a reduced natural uranium evolution is spotted due to a slower than necessary deployment of nuclear power park. The annual enrichment needs, again essentially as function of the sampled burnups for the UOX/MOX fuels, is shown in Fig. 3.36. The complete case study can be found in Annex V on the CD-ROM accompanying this publication.

3.1.5.5. Conclusions

Within these scenarios, not each of the EU27 Member States will embark on EPR MOX use and therefore synergies can be considered where a recycling platform, as Sellafield and La Hague were and where La Hague still is, provides the fuel cycle services to many of the EU27 Member States. The previous figures show the gain in spent fuel and HLW arising from such scenarios and thus the reduced geological disposal volume or surface required.

3.1.6. Comparative assessment of collaborative fuel cycle options for Indonesia

3.1.6.1. Introduction

The introduction of nuclear energy in Indonesia is not considered only to reach an optimum energy mix with regard to costs and the environment, but also to relieve the pressure arising from the increasing domestic demand for oil and gas (as oil and gas resources can be used for export and feed stocks). Thus, the role of nuclear power in Indonesia is to stabilize the supply of electricity, conserve strategic oil and gas resources, and protect the environment from harmful pollutants resulting from the use of fossil fuels.

Considering the projected energy generation for the CO_2 limitation scenario and the role of nuclear in the energy mix as calculated by the Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) low carbon scenario, nuclear power will enter into the energy mix in 2024 with an installed capacity of 2000 MW(e), and is anticipated to grow up to 36 000 MW(e) by 2050. The inclusion of nuclear energy in the energy mix sets the ground for the need of sustainable planning of the country's nuclear power plant programme into the future. In order to support the long term sustainability of nuclear power plant development in Indonesia, this study analyses a range of fuel cycle options from the perspective of their effect on the utilization of natural uranium resources and the radioactive waste generated (i.e. spent fuels).

This study is associated with the objective of INPRO SYNERGIES Task 1, on the evaluation of synergistic collaborative scenarios of fuel cycle infrastructure development. The complete case study can be found in Annex II on the CD-ROM accompanying this publication.

3.1.6.2. Objective and problem formulation

The objectives of this study are to assess the most viable option of fuel cycle strategies to support the sustainability of nuclear power plant implementation in Indonesia, based on the potential of national, regional and international arrangements for fuel cycle. The assessment results could be used to support the preparation of nuclear fuel cycle policy, to develop awareness of long term issues surrounding the nuclear power programme, and to support strategic planning and decision making for the development and deployment of a nuclear power plant programme in a sustainable manner.

Five options of nuclear fuel cycles were evaluated in order to support the sustainability of nuclear power in Indonesia:

(1) Once through fuel cycle. This reference fuel cycle assumes the electricity production of 1000 MW(e)·year of PWRs with conventional UO_2 fuel, and the direct disposal of spent nuclear fuel in a geological repository.
(2) Plutonium mono-recycling with MOX fuel in PWRs. This fuel cycle incorporates conventional reprocessing of LWR fuel (e.g. the one used in some countries in Europe and Asia). The recycle scheme for plutonium is based on the use of 1000 MW(e) PWRs using UO_2 fuel. The spent UO_2 fuel is processed using the conventional PUREX process. The separated plutonium is recycled in the form of uranium–plutonium MOX fuel in PWRs. This fuel cycle provides for disposal of the HLW resulting from the PUREX process and direct disposal of MOX spent fuel in a geological repository.
(3) Direct use of spent PWR fuel in CANDU reactors (DUPIC). This fuel cycle is based upon dry thermal and mechanical processes to directly fabricate CANDU (Canada deuterium–uranium) fuel from spent PWR fuel material without separating the fissile material and fission products. This concept was proposed and termed the DUPIC fuel cycle in a joint development programme involving the Korea Atomic Energy Research Institute (KAERI), Atomic Energy of Canada Limited (AECL) and the United States Department of State

in 1991. Since then, KAERI, AECL and the United States, with the participation of the IAEA, have been engaged in a practical exercise to verify the concept.

(4) Synergistic fuel cycle of LWR–fast reactor. This is a 'classical' synergy assuming fast reactor fuel is based on reprocessed fuel of LWR containing uranium and transuranics, which fast reactor could effectively burn owing to its high neutron flux and good neutron economy. Being started like that, fast reactors could then operate in closed fuel cycle, recycling its own discharges, among other things. The non-consumed uranium from LWR spent fuel could then be disposed, presumably, in a more simple way compared to direct disposal of spent fuel. This case is basic in emerging fast reactor programmes of nearly all interested countries [3.24].

(5) Once through thorium–uranium fuel in PWRs. The very attractive neutronic characteristics in thermal spectrum of LWRs of ^{233}U–thorium fuel is on account of the favourable fission to capture cross-section ratio. Such fuel is thus sometimes being considered as an alternative fuel for present day PWRs, where it could help improve burnup characteristics and plant economy. The use of ^{233}U–thorium fuel could also contribute to a decreased long term radiotoxicity of spent fuel owing to smaller minor actinide generation rate inherent to the uranium–thorium fuel cycle [3.12].

3.1.6.3. Assumptions, methods, codes and input data used

The comparison of different nuclear fuel cycle options has become an integral element to any analysis of the future prospects for nuclear energy in Indonesia. The evaluation metrics used to evaluate and compare include: resource utilization, waste production, proliferation risk and fuel cycle cost. Resources utilization is measured as the mass of natural uranium (or thorium) required per unit energy generated. Waste production is measured using two metrics: the mass of transuranics and the mass of fission products discharged per unit energy generated. The proliferation risk posed any given fuel cycle is difficult to quantify, therefore to avoid these difficulties, the study continued the inventories of plutonium and transuranics per unit energy generated. A fuel cycle cost metric was used to capture the impact of advanced fuel cycles on the costs of fuel alone.

Mass flow calculations were performed based on data publicly available [3.9, 3.25, 3.26]. For simplicity, only equilibrium conditions were considered. The current once through cycle of medium burnup (51 GW·d/t HM) was used as a baseline in the study; and all mass flow calculations were represented for the production of 1 GW(e)·year of electricity. The analysis was only restricted to the equilibrium state of the fuel cycle schemes. The data used in the study regarding processes and material flows for each fuel cycle scheme considered are drawn from published literature. For fuel cost analysis, a simplicity model of a Massachusetts Institute of Technology study was used [3.27]. The main input data used is summarized in Table 3.17.

3.1.6.4. Summary presentation and analysis of the results

A summary is presented in Fig. 3.37 and Table 3.18.

(a) Resource utilization

Resource utilization is strictly linked to the environmental component of sustainable development. A nuclear system should be able to generate energy while making efficient use of fissile/fertile material and other non-renewable materials and without giving rise to a substantial degradation of these resources. Hence long term availability, and efficient use, of resources are a key component of sustainability.

The analysis results indicate that PWRs on the once through UOX fuel cycle utilize uranium resources inefficiently, while the once through thorium–uranium fuel cycle consumes uranium resources at an even higher rate. In comparison, the synergistic fuel cycle with PWRs and fast reactors utilizes uranium resources more efficiently, but the gains in uranium utilization are not significant.

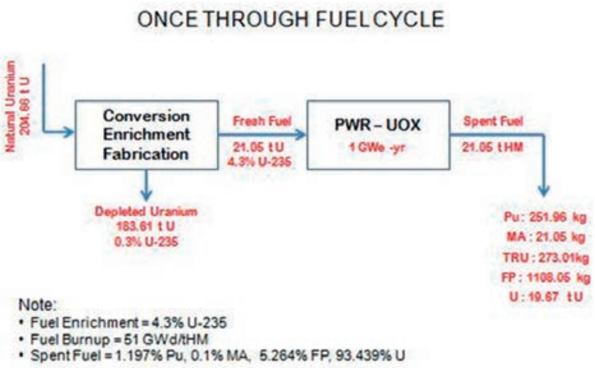
Among the pure thermal reactor strategies, the DUPIC fuel cycle — which utilizes CANDU reactors with better neutron economy compared to PWR reactors – is the only strategy which offers significant savings in uranium demand. Both the DUPIC and PWR–fast reactor cycle are still under development and not yet available in the commercial market.

Uranium resources are sufficient to support the moderate growth of nuclear power plant capacity until the mid 21st century (according to the GAINS study). The significant reduction of natural uranium demand could be

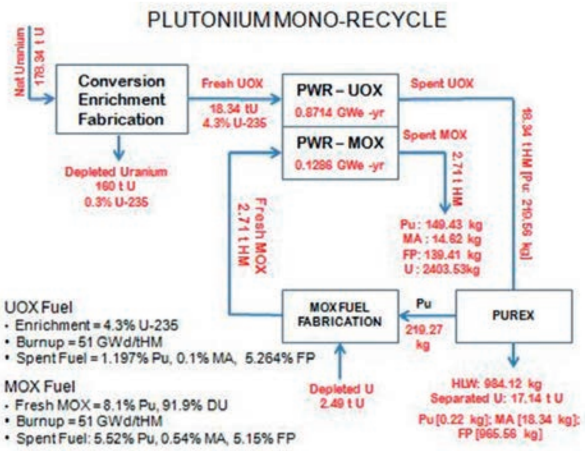
TABLE 3.17. MAIN INPUT DATA

Item	Condition
Fuel discharge burnup	PWR (UOX, MOX): 51 GW d/t HM CANDU (DUPIC): 14 GW d/t HM Fast reactor: 140 GW d/t HM
Reactor thermal efficiency	PWR: 34% PHWR: 33% Fast reactor: 40%
Fresh fuel composition	PWR: UO_2, 4.3% ^{235}U [PWR] CANDU (DUPIC): UOX from PWR SF PWR (MOX): 8.1% Pu, 91.9% depleted U [Pu mono-recycle in PWR] Fast reactor: 66.84% U, 33.16% TRU [metallic fuel] Seed assembly of Th–U fuel: UOX, 20% ^{235}U Blanket assembly of Th–U cycle: $[U,Th]O_2$, 87% ThO_2, 13% UO_2 [10% ^{235}U]
Spent fuel composition	PWR (once through cycle): 1.197% Pu, 0.51% MA, 5.264% FP, 93.439% U PWR (MOX) [Pu mono-recycle]: 5.52% Pu, 0.54% MA, 5.15% FP DUPIC: 0.8379% Pu, 0.12% MA, 6.7091% FP, 0.9233% U Fast reactor: 59.94% U, 26.46% TRU, 14.1% FP Seed assembly of Th–U fuel: 1.97% TRU, 1.56% Pu, 14.5% FP Blanket assembly of Th–U fuel: 0.51% TRU, 0.45% Pu, 8.8% FP
Fuel cost data: front end	Natural uranium: US $80/kg HM Conversion: US $10/kg HM U enrichment: US $120/kg SWU UOX fuel fabrication: US $275/kg HM MOX fuel fabrication: US $1500/kg HM DUPIC fabrication: US $850/kg HM Fast reactor fuel fabrication: US $2500/kg HM Th–U fuel fabrication: US $275/kg HM
Fuel cost data: back end	PWR (UO_2, MOX) SFDS: US $250/kg HM PWR ($UO_2$) SF reprocessing: US $1000/kg HM HLW storage and disposal: US $200/kg HM DUPIC SFDS: US $250/kg HM Advance PUREX: US $1000/kg HM Reprocessing losses of 0.1% are assumed for all fuel type reprocessing methods
Fuel service: lead time	Natural U purchase: 24 months Conversion service: 20 months Enrichment service: 18 months Fuel fabrication: 12 months SF reprocessing (PUREX): 24 months DUPIC fuel fabrication: 24 months
Fuel service: lag time	SFDS: 5 years
Others	^{235}U in natural uranium: 0.007 114 Tail assay in enrichment service: 0.3 No material losses in uranium conversion and fuel fabrication SF cooling time prior to reprocessing: >5 years

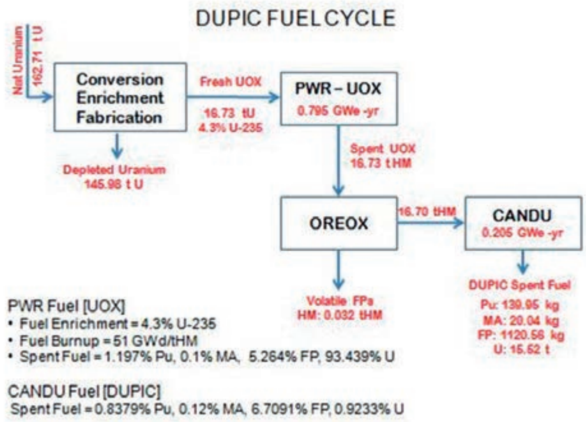
Note: CANDU — Canada deuterium–uranium; DUPIC — direct use of spent PWR fuel in CANDU reactors; FP — fission product; HM — heavy metal; HLW — high level waste; MA — minor actinide; MOX — mixed oxide; PHWR — pressurized heavy water reactor; PUREX — plutonium and uranium recovery by extraction; PWR — pressurized water reactor; SF — spent fuel; SFDS — spent fuel dry storage; SWU — separative work unit; TRU — transuranic; UOX — uranium oxide.



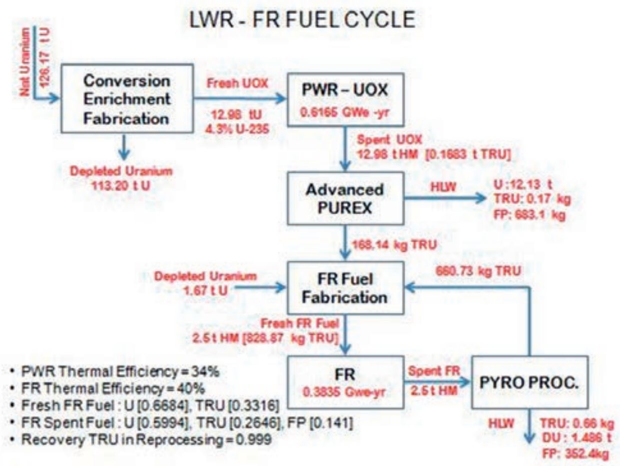
(a) Once through



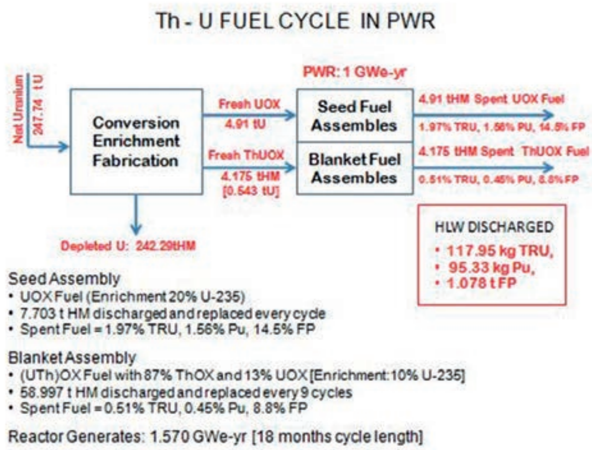
(b) Plutonium mono-recycle



(c) DUPIC



(d)) Light water reactor–fast reactor



(e) Thorium–uranium

FIG. 3.37. Mass flow analysis results for fuel cycle considered (all quantities are per GW(e)·year).

TABLE 3.18. SUMMARY OF ANALYSED RESULTS (COMPARATIVE TABLE)

Fuel cycle metrics	Once through	Pu mono-recycle	DUPIC	PWR–FR	Th–U
Resources utilization (t HM/GW(e)·year)					
Natural U consumption	204.66	178.34	162.71	126.17	247.74
High level waste (kg HM/GW(e)·year)					
TRU discharge	273.01	182.61	159.99	0.83	117.95
FP discharge	1108.05	1104.97	1120.56	1035.5	1078.0
Proliferation (kg HM/GW(e)·year)					
Pu discharge	251.96	149.65	139.95	NC	95.33
Separated Pu	—	219.27	—	—	—
TRU discharge	273.01	182.61	159.99	0.83	117.95
Reprocessing rate (t HM/GW(e)·year)	—	18.34	(16.73)	15.48	—
Economic (US $mil/kW·h)					
Fuel cost of NPP park	6.347	8.481	6.648	7.699	8.054

Note: DUPIC — direct use of spent PWR fuel in CANDU reactors; FP — fission product; FR — fast reactor; HM — heavy metal; NC — not calculated; NPP — nuclear power plant; SF — spent fuel; SFDS — spent fuel dry storage; SWU — separative work unit; TRU — transuranic.

performed by incorporating fast reactors into the reactor mix; the reduction would correspond approximately to the percentage of fast reactors in the mix. Considering the current size of the depleted uranium stock, any fast reactors which could be constructed in this century would not depend on the availability of natural uranium.

(b) Waste production

Reference [3.28] points to problems in evaluating the adverse impacts of radioactive waste on the environment. The mobility of radioactive isotopes is mentioned as an important factor defining the hazard, it is also noted that radiotoxicity of fission products in longer term is several orders of magnitude less compared to actinides. Nevertheless, according to Ref. [3.28] these are the fission products that difine radiological hazard of spent nuclear fuel repository in the first hundreds of thousands of years, just because their mobility is higher as compared to actinides.

From the waste production point of view, the synergistic PWR–fast reactor scenario is the best choice among the fuel cycles considered. This fuel cycle discharges transuranic elements and fission products at a much lower rate per unit energy generated (electricity). The DUPIC cycle is expected to discharge more transuranic elements and fission products per unit energy generated owing to extended burnup of UOX fuel in CANDU reactors. Although both the single pass plutonium recycling MOX fuel and once through cycle of uranium–thorium are expected to have modest discharges of transuranic elements and fission products per unit energy generated, there is no clear advantage for fission product transmutation (i.e. no fuel cycle is a clear champion in minimizing fission product discharge rates).

The rate of fission product discharge for synergistic PWR–fast reactor fuel cycle is somewhat lower than that of PWR once through fuel cycle. This is because of a contribution of fast reactors to increased thermal efficiency of the whole reactor fleet. However, the corresponding effect has its clear limit because increase in thermodynamic cycle efficiency is limited by around 50%. Which means the discharge rates could be at best reduced by 50% compared to present day LWRs.

If commericial availability is to be considered, the synergistic PWR–fast reactor fuel cycle is the best option based on the rate of specific discharge of transuranic elements and fission products. This is also the best option if the selection process assigns high importance to uranium resources. However, if residual uranium is not considered as a resource for future fast reactors, its long term radiological impact has to be considered as an integral part of waste management, due to the fact that uranium decay products always dominate global radiotoxicity in the very long term.

(c) Non-proliferation

No nuclear fuel cycle is free from the risk of proliferation, but separation of plutonium from spent nuclear fuel is traditionally viewed as one of the most dangerous activities within commercial nuclear fuel cycles from a proliferation risk perspective. Working inventory of around 219.27 kg/year is required at any given time for a signle recycle of plutonium. To put in perspective, a 1000 MW(e) PWR would produce aquantity of plutonium sufficient to make about 22 nuclear weapons.

The plutonium present in the repository is also of proliferation concern. A PWR operating in a once through nuclear fuel cycle 'delivers' 251.96 kg/GW(e)·year of plutonium to the repository. This quantity is huge compared to the 10 kg plutonium needed for a nuclear weapon.

Limited (single) recycle of spent fuel or even a once through uranium–thorium cycle in LWRs (Radkowsky thorium fuel) cannot reduce the content of plutonium in spent fuel even by one order of magnitude and therefore the advantage offered by them with respect to proliferation risk reduction cannot be rated as significant. In general, high burnup fuel contains the plutonium that is less attractive for nuclear weapon progammes owing to higher content of ^{238}Pu, a neutron and alpha emitted with huge decay heat.

When multiple recycling of spent nuclear fuel is performed (e.g. in a PWR–fast reactor NES), only traces of plutonium are likely to come to the repository (<1 kg/GW(e)·year of transuranics). In this case, both the low content of the plutonium and a high degree of its dilution in HLW offer a meaningful barrier to proliferation [3.28].

(d) Economics of the fuel cycle

The fuel cost contribution to the total cost of nuclear electricity generation is known to be small. Fuel cycle costs are in the range of 10–20% of the total, with waste management accounting for only 1–5 % of the total. While waste management costs vary significantly among strategies, their contribution to total generation costs is small enough to prevent it from being a major driving factor in decision making.

With regard to the costs of specific fuel cycle options, they are known to be lowest for once through fuel cycles with conventional thermal spectrum reactors. A fuel cycle with only physical processing of spent fuel, such as DUPIC, is also expected to result in low cost, being cheaper compared to closed fuel cycles with chemical reprocessing. With respect to the latter, the uranium price is a factor affecting competitiveness, but its impact is known to be moderate when compared to the cost of the processes and facilities of a closed fuel cycle. According to Ref. [3.28]:

> "the lower spent fuel and plutonium discharge rates and degraded plutonium isotopics afforded by this concept are not rewarded under the current system of nuclear waste management. Thus there is no incentive for nuclear plant operators to incur the expenses associated with developing thorium fuels and refitting LWR cores to accommodate seed and blanket assemblies.
>
> "...the benefits from these fuel cycles...are insufficient to change the prospects for nuclear energy considerably."

3.1.6.5. Conclusions

Considering uranium utilization, it can be concluded that until the mid 21st century, a once through UOX fuel cycle with PWRs is the most viable option to support the nuclear power programme in Indonesia in a sustainable manner. If available uranium becomes scarce (or there are problems with spent fuel management), the implementation of a limited recycle option with a single recycle of MOX fuel could be considered. Proven technology to recycle plutonium from used UOX fuel exists in the commercial market now and may become much cheaper in the future.

The single pass MOX fuel recycling offers some uranium resource saving. In addition, the waste production per unit energy generated is lower than waste production in a once through UOX fuel cycle. However, this fuel cycle poses a larger proliferation risk owing to substantial working inventory of separated plutonium. Coupled with fast reactors (PWR–fast reactor strategy), this fuel cycle could become more attractive in the future.

3.1.7. Analysis of ALWR based scenario

3.1.7.1. Introduction

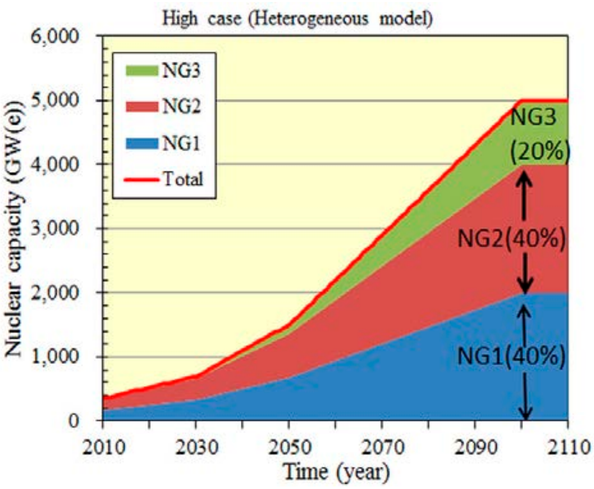
The analysis method using the heterogeneous world model that considers the synergy among groups with different nuclear energy policies, instead of using the homogeneous world model, is expected to be one of the realistic simulations. This section provides a summary of the heterogeneous world model analysis carried out with the Japanese FAMILY-21 code on the advanced light water reactor (ALWR) based scenario, one of the themes of Task 2.

An analysis was performed for the purpose of checking adaptability of FAMILY-21 to the scenario analysis with the heterogeneous world model. At the same time, impacts on key indicators identified in the comparison between the homogeneous world model and heterogeneous world model were investigated. The complete case study can be found in Annex XX on the CD-ROM accompanying this publication.

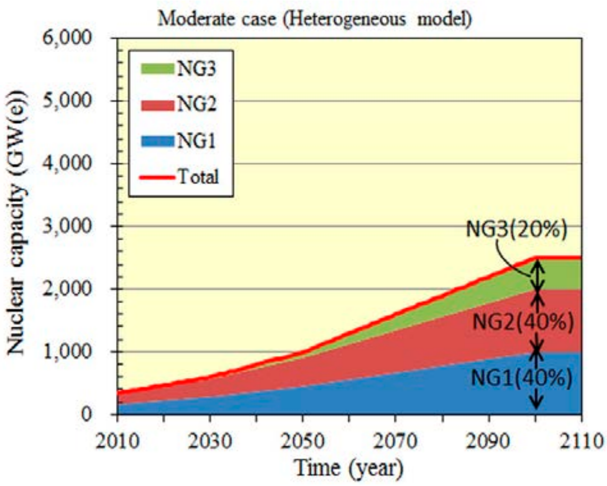
3.1.7.2. Objective and problem formulation

The analysis of the ALWR based scenario with the Japanese FAMILY-21 code was performed for the purpose of checking the adaptability of the code to a scenario involving the heterogeneous introduction of NESs on a global scale. Furthermore, key indicators, such as LWR MOX reactor capacity, reprocessing capacity, cumulative natural uranium demand, spent fuel stockpile, and HLW disposal volume were investigated to grasp the disparity and characteristics differentiating between the homogeneous world model and the heterogeneous world model.

As two global models, a homogeneous world model assumed convergent as a single nuclear power policy. In a heterogeneous world model, a non-geographical group (NG1) assumed plutonium recycling in thermal reactors, an uncertain nuclear fuel cycle policy in NG2, and use of thermal reactors in a once through option in NG3 of newcomer countries. In this partially synergistic mode, the spent fuel of NG2 is transported to the NG1, and reprocessing and plutonium recycling are performed in NG1. In the non-synergies mode, each group of NG1, NG2, NG3 are independent and assumed that transport of spent fuel and nuclear fuel materials are not carried out between groups. The evaluation was carried out on the nuclear power generation capacity with two growth patterns considered in GAINS (see Fig. 3.38). In this evaluation, eight cases shown in Table 3.19 were computed using FAMILY-21. The spent fuel of NG2 is reprocessed in NG1, and recovered plutonium is utilized in thermal reactors of NG1.



(a) High case



(b) Moderate case

FIG. 3.38. The standard growth curve of nuclear capacity examined in the GAINS project.

TABLE 3.19. EVALUATION CASES

Scenario		Recycling of spent fuel			Nuclear capacity	
Model	Option for sent fuels (mode*)	NG1	NG2	NG3	High	Moderate
Homogeneous	Once through		No		X	X
	Pu mono-recycling		Yes		X	X
Heterogeneous	Pu mono-recycling (partially)	Yes	No*	No	X	X
	Pu mono-recycling (non)	Yes	No	No	X	X

* Mode: partially — partially synergistic; non — non-synergistic.

3.1.7.3. Assumptions, methods, codes and input data used

The main assumptions for the ALWR scenario analysis are listed in Table 3.20, and were set based on public documents and a study of the Technical Subcommittee established by the Japan Atomic Energy Commission [3.29–3.32]. The analysis of the ALWR based scenario was conducted through the use of the Japan Atomic Energy Agency calculation code FAMILY-21, developed to quantitatively assess the adaptability of the reactor system and its fuel cycle to future uncertain nuclear needs. This code has two advantages: its usability and the function to calculate the change of the isotopic composition of the nuclear fuel material by the code itself. In addition, FAMILY-21 has experience in benchmarking other scenario analysis codes [3.33, 3.34].

3.1.7.4. Summary presentation and analysis of the results

In this summary, the analysis results are shown with the sum of the calculation results for three groups in the heterogeneous world model — NG1, NG2 and NG3. Results of each group are described in Annex XX on the CD-ROM accompanying this publication.

ALWR MOX installation capacities of each case are shown in Fig. 3.39. In the homogeneous model, the ALWR MOX share was about 37–38% of total global installed capacity, and it was approximately equal to the nuclear capacity of NG1. In the heterogeneous partially synergistic mode, the ALWR MOX share was about 24–25% of the world's total installed capacity, and it was approximately equal to about 61–63% of the nuclear capacity of NG1. Similarly in the heterogeneous non-synergistic mode, the ALWR MOX share was about 15–16% of the world's total installed capacity, and it was approximately equal to about 38–40% of the nuclear capacity of NG1.

Reprocessing capacities of each case are shown in Fig. 3.40. Reprocessing capacity by 2020 is based on plants in operation and in the planning phase in each country (6100 t HM: THORP, United Kingdom; UP-2, UP-3, RT-1 and future planned reactors in the Russian Federation, China and Japan). Reprocessing capacity after 2020 increases roughly in proportion to new fuel demand. In the high case of nuclear capacity in 2110, reprocessing capacity was about 63 000 t/year with the homogeneous model, about 42 000 t/year with the heterogeneous partially synergistic mode, and about 27 000 t/year with the heterogeneous non-synergistic mode. In the moderate case, the reprocessing capacities in 2110 were about half of those of the high case. The reprocessing capacity of the homogeneous model became about 32 000 t/year, the heterogeneous partially synergistic model was about 20 000 t/year, and about 13 000 t/year with the heterogeneous non-synergistic mode.

Cumulative natural uranium demands of each case are shown in Fig. 3.41. In the homogeneous model, about 10% of natural uranium demands with both high case and moderate case in 2110 were saved by introducing ALWR MOX. Meanwhile, the natural uranium demands in the heterogeneous model increase slightly compared to those of the homogeneous model because of the decrease of the ALWR MOX share. In the ALWR based scenario, the saving quantity of the natural uranium was proportional to the ALWR MOX share.

Spent fuel stockpiles of each case are shown in Fig. 3.42. In the homogeneous model, the spent fuel stockpiles of the plutonium mono-recycling case were about half in comparison with the once through case in 2110 by the introduction of the reprocessing. The spent fuel stockpiles of the heterogeneous model in 2110 decrease by about half of those of the homogeneous model because of the decrease of reprocessing capacity. The spent fuel transported to the disposal site is excluded from these calculation results.

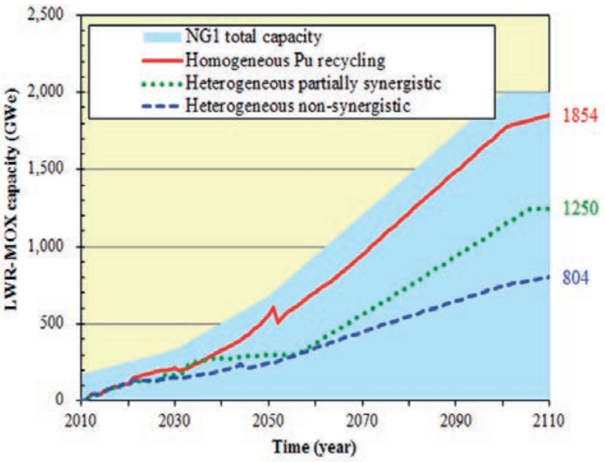
TABLE 3.20. MAJOR ASSUMPTIONS

Item	Condition	Ref.
Reactor		
Average discharged burnup	PWR: 49 GW·d/t APWR: 60 GW·d/t HWR: 7.0 GW·d/t	[3.29] [a]
MOX use in LWRs	1/3 MOX fuel assemblies	[3.29]
Effective full power days	PWR: 1300 APWR: 1592 HWR: 292	[3.29] [a]
Lifetime/load factor	60 years/85%	[a]
Conversion/enrichment		
Lead time/loss rate	2 years/1%	[3.30, 3.31]
Tails assay	0.2%	[a]
Fuel fabrication		
Lead time/loss rate	1 year/1%	[3.30, 3.31]
Reprocessing		
Cooling time/loss rate	5 years (minimum), U/Pu: 2%	[a]
Treatment of recovered materials	Without reuse of recovered U and minor actinides	[a]
Waste storage		
Intermediate storage period	50 years	[3.29]
Geological repository		
Disposal volume per fuel mass	4.52 m^3/package (canister for spent fuel) 0.91 m^3/package(over-pack for vitrified waste) (Upright position hard rock)	[a]
Deployment year	2025 (Canister) 2047 (Vitrified waste)	[3.29]
Initial inventory in 2010		
Spent fuel	ca. 250 000 t HM (incl. ca. 500 t U HWR spent fuel)	[3.30, 3.31]
Pu	ca. 256 t HM	[3.32]
Vitrified waste	ca. 560 000 packages	[a]

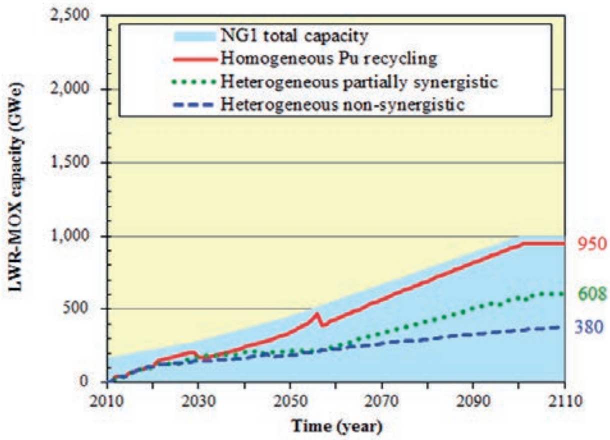
[a] Information based on a study performed in Japan by the Technical Subcommittee on Nuclear Power, Nuclear Fuel Cycle.

Note: (A)PWR — (advanced) pressurized water reactor; HM — heavy metal; HWR — heavy water reactor; LWR — light water reactor; MOX — mixed oxide.

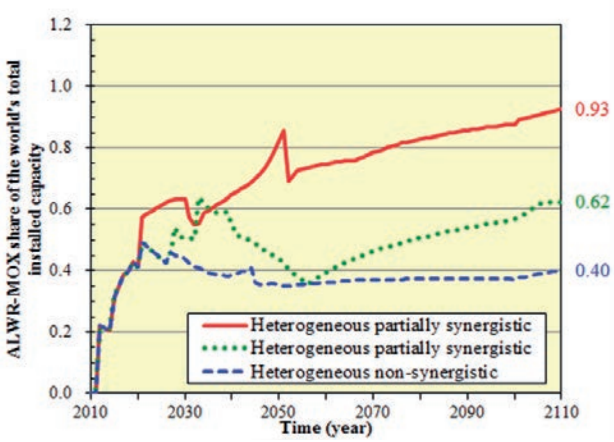
HLW disposal volumes of each case are shown in Fig. 3.43. In the homogeneous model, HLW volume is reduced by plutonium mono-recycling for the introduction of ALWR MOX reactor because it was processed into vitrified glass, which is more compact than spent fuel. The reduction of HLW volume with the heterogeneous model is about half of the homogeneous model. A longer evaluation period is needed to evaluate effects on HLW volume because the effect caused by capacities of reactor and reprocessing plants is shown after around 2064 (i.e. a long term storage period of 50 years is needed before final disposal).



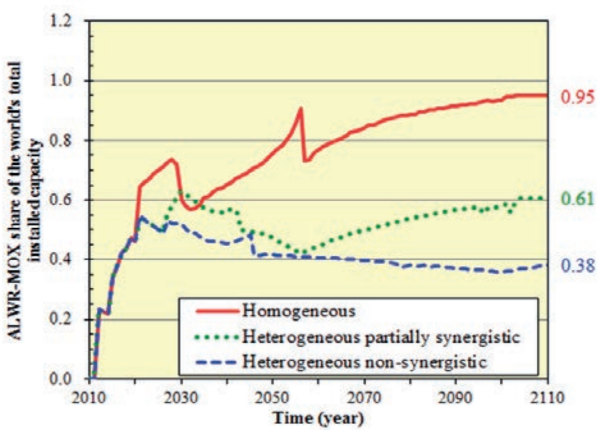
(a) High case



(b) Moderate case

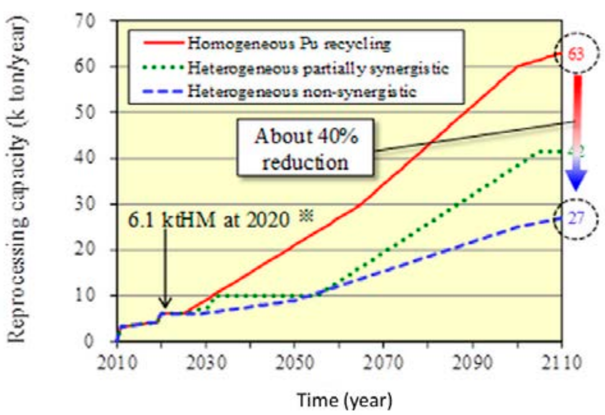


(c) High case

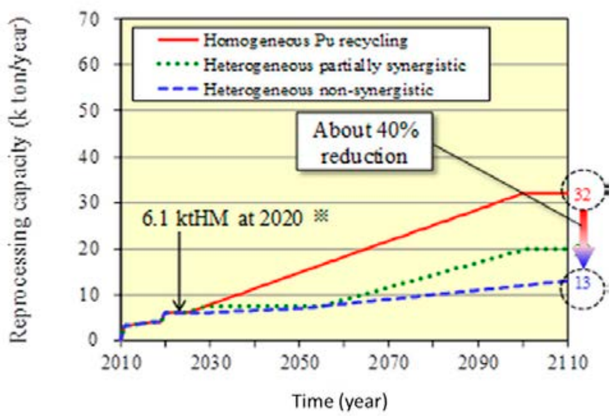


(d)) Moderate case

FIG. 3.39. Advanced light water reactor mixed oxide installed capacity and share of the world's total installed capacity.

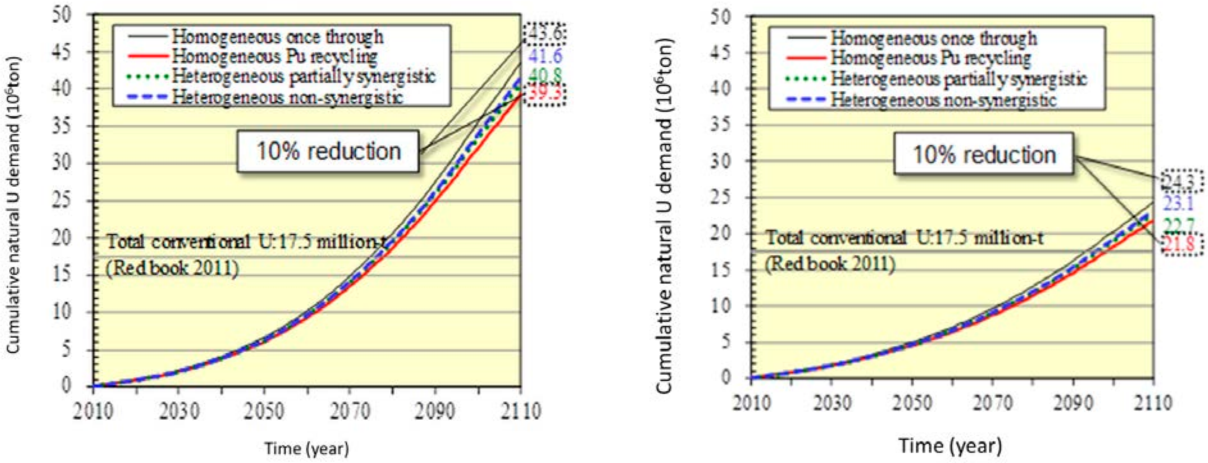


(a) High case



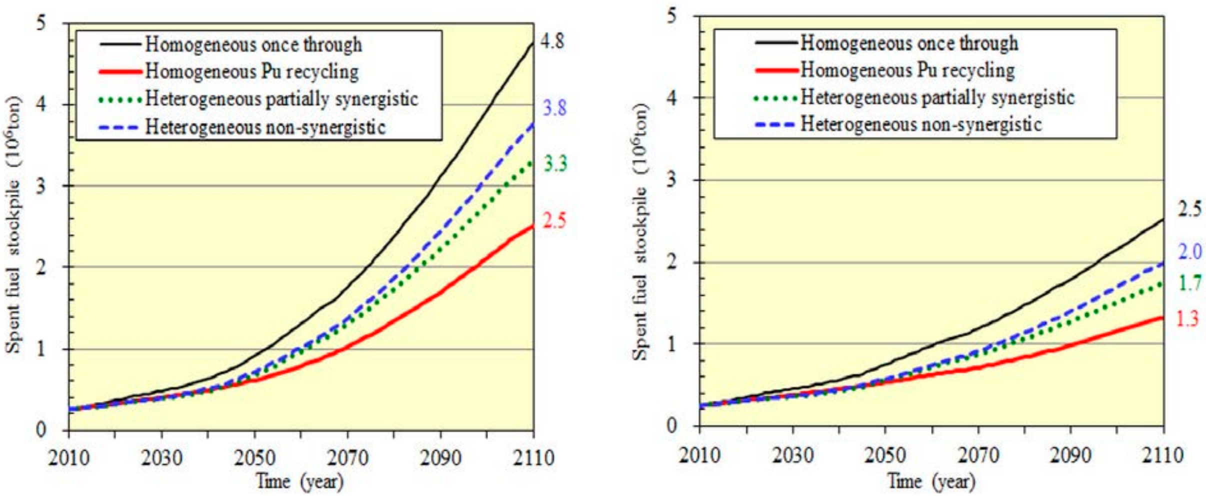
(b) Moderate case

FIG. 3.40. Reprocessing capacity.



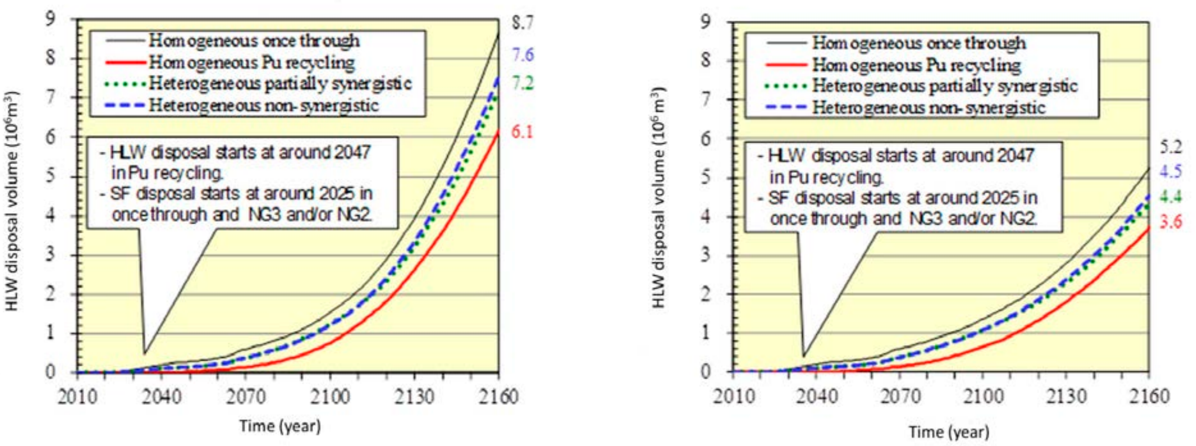
(a) High case (b) Moderate case

FIG. 3.41. Cumulative natural uranium demand.



(a) High case (b) Moderate case

FIG. 3.42. Spent fuel stockpile.



(a) High case (b) Moderate case

FIG. 3.43. High level waste (spent fuel and vitrified waste) disposal volume.

3.1.7.5. Conclusions

The analysis of the ALWR base scenario was conducted using the Japanese calculation code FAMILY-21. This evaluation revealed that in the heterogeneous world model the ALWR MOX share, reprocessing capacity and HLW volume reduction are about half of those of the homogeneous world model. In other words the homogeneous world model is suitable for analysing the biggest impact of an adopted scenario, while the heterogeneous world model is effective for evaluations considering future uncertainty.

3.1.8. National Romanian scenarios with reliance on domestic and imported U/fuel supply, by considering regional collaboration in nuclear fuel cycle and including economic analysis

3.1.8.1. Introduction

The Romanian study was included as Scenario A.3 (Scenario family A: LWR uranium–plutonium mono-recycling) under INPRO Task 1, on evaluation of synergistic collaborative scenarios of fuel cycle infrastructure development of the SYNERGIES collaborative project. The analyses included in the case study have been performed by the team of experts from the Technologies for Nuclear Energy State Owned Company (Regia Autonomă Tehnologii pentru Energia Nucleară, RATEN), Institute for Nuclear Research Piteşti (Institutul de Cercetari Nucleare, ICN Piteşti) and addresses essentially, in a 'win-win' situation, the short term issues and challenges Romania may face today and in the nearby future, while providing prospects to the medium and longer term.

The Romanian study proposes to evaluate and analyse the development of the nuclear capacity and increasing of its share in the national energy mix in order to assure the sustainability, keeping options open to the future while bringing solutions to short and medium term challenges, according to the objective of the INPRO SYNERGIES collaborative project. By considering regional collaborative architectures both in the front end and back end of the nuclear fuel cycle, the study offers the possibility to identify viable collaboration options for development of the national nuclear energy strategies, based on the 'win-win' approach. More details can be found in Annex V on the CD-ROM accompanying this publication and the work in Ref. [3.35].

3.1.8.2. Objective and problem formulation

The Romanian study propose as a main objective the assessment of possible scenarios, including collaboration both in front end and back end of the nuclear fuel cycle based on the 'win-win' approach and the current existing and near term projected technologies and infrastructure. In order to provide a substantial technical support for the decision making with regard to a comprehensive and responsible national nuclear energy strategy on medium term envisaging the transition to long term globally sustainable NES, an economic analysis using the suggested Task 1 key indicators is performed. The long range objective addressed by the study is the global vision of the national collaboration options for energy sustainability in regional and global context.

The Romanian nuclear programme started in 1950. Two research reactors were commissioned: the VVR-S in 1957 (decommissioning started in 1997) and the TRIGA 14 MW(e) in 1979. Romania's current policy is for a once through nuclear fuel cycle based on indigenous facilities, without enrichment or reprocessing (which are prohibited by national laws). The front end activities are carried on in the uranium ore mines, Feldioara UO_2 powder plant, nuclear fuel plant from Piteşti and the heavy water plant. The nuclear electricity generation is assured by the operation of Cernavodă nuclear power plant with two PHWR reactors, CANDU 6 type (700 MW(e) each, Unit 1 since December 1996 and Unit 2 since 2007). The management of spent nuclear fuel at the Cernavodă nuclear power plant is assured by the interim wet storage in the spent fuel bay (for at least six years), interim dry storage, Canadian MACSTORE type (for 30 years; first module became operational in 2003) and interim storage for solid radioactive waste. Final disposal of low level waste (LLW) and intermediate level waste (ILW) from the Cernavodă nuclear power plant (currently in stage of site authorization) is based on a near surface repository with multiple barriers (Saligny site, inside the nuclear power plant exclusion zone). Research is carried on the geological environment for spent nuclear fuel and HLW deep geological repository (very preliminary stage). The national repository for LLW and ILW at Baita has been in operation since 1985.

Romania has a balanced portfolio of electric energy generation capacity comprising hydro, nuclear, coal and gas fired power plants, with renewable (other than hydropower) representing a small but rapidly growing subsector of the generation market. The electricity generated by the Cernavodă nuclear power plant represents about 20% of the national electricity production. The Romanian electricity generation sector is facing major challenges as a significant percentage of the generation assets are already past their useful technical life (30% are about 40 years old). Taking into account that around 28% (5.5 GW(e)) of the total installed capacity needs to be replaced by 2020 and around 55% (11 GW(e)) by 2035, the Government considers nuclear power as a stable component of the national energy mix taking into consideration security of supply, reliability, economic efficiency, and greenhouse gas low emissions.[6]

The key questions to be answered were:

— What is the potential of nuclear energy to participate with an important share in the national energy mix, according to the strategic documents in force, in conditions of cost competitiveness, safety and security of supply, with assurance of the projected national electricity demand?
— What is the impact of considered scenarios on the national energy mix portfolio of capacities and electricity production?
— What is the impact of considered scenarios on the domestic resources of uranium?
— What is the economic projection of considered scenarios in terms of investments needed for new nuclear capacities addition?
— What are the implications of each considered scenario on the level of fresh fuel requirements for nuclear capacities?
— Which are the amounts of spent nuclear fuel annually discharged from the reactors and transferred to interim wet storage for cooling?
— What is the cumulative spent nuclear fuel volume in interim dry storage?
— What is the impact of various discount rates on the annual evolution of interest parameters, until reaching the considered time horizon for modelling?
— What is the impact of CANDU Units 1 and 2 extended time life on the presence and operation timing of nuclear capacities in the national energy mix, uranium resources consumption, uranium and fresh fuel requirements, spent fuel volume in interim dry storages?

The study was focused on the modelling of national NES development in short and medium terms, considering existing nuclear fuel cycle infrastructure, provisions of strategic documents in force and including also the possibility of regional collaboration related to uranium and fresh fuel supply and spent fuel storage, in order to consolidate the nuclear energy role and increase its share in the energy sector envisaging the long term national and regional energy sustainability. The case study analyses were performed for three distinct NES development scenarios:

(i) Basic case: Four PHWR, CANDU type (existing CANDU Units 1 and 2, 700 MW(e) each, in operation, and new CANDU Units 3 and 4, 720 MW(e) each, with projected in-service after 2020).
(ii) Pessimistic case: Two PHWR, CANDU type (existing CANDU Units 1 and 2, in operation).
(iii) Optimistic case: Four PHWR, CANDU type (as in the basic case) and another nuclear power plant, advanced PWR (1000 MW(e)) or advanced PHWR (enhanced CANDU, 720 MW(e)), the projected in-service being after 2035.

For sensitivity analyses, three variation factors were considered:

— Annual electricity demand[7].
— Annual discount rate (5%, 8% and 10%). An 8% discount rate was considered the most appropriate for Romania’s conditions and its economic and financial environment.
— CANDU Units 1 and 2 lifetime (35 years with the possibility of extension to 40 years of operation).

[6] See Decision No. 1069, Romanian Energy Strategy for 2007–2020, Ministry of Economy and Finances, Official Bulletin No. 781/19.11.2007.

[7] According to a 2012 study regarding the development directions of Romanian Electricity Transport Network for 2011–2035 by the Institute for Studies and Power Engineering (ISPE).

3.1.8.3. Assumptions, methods, codes and input data used

Romania's energy sector was modelled taking into account existing electricity generating capacities at the level of 2011, the time horizon for the performed analysis being 2050. The national energy mix kept its balance characteristics including the corresponding specific producers of electricity: classical power plants based on fossil fuels (coal fired power plants, gas fired power plants and combined cycle power plants, producing electricity and heat), nuclear power plants and renewable energy power plants (including hydro, wind farms and solar photovoltaic stations).

The case study considered both using of the existing domestic natural resources and import of resources, if necessary, at international market prices. Abundant domestic resources exist for coal fired and hydro power plants, and also the appropriate corresponding mining capability to cover the modelled period in present study. The import of coal was still allowed, if needed. The share of natural gas in the power generation sector is relatively low because a significant part of natural gas consumption is sourced from imports. The renewable energy sources contribution have been considered according to the strategic documents in force.[8]

For the electricity demand evolution, two pessimistic scenarios from the ISPE study for 2011–2035 were considered (see Fig. 3.44). These scenarios were elaborated based on GDP evolution outlooks realized by the National Institute for Economic Studies (2010–2014) and National Commission for Prognoses (2010–2020–2030). Another energy demand evolution scenario — the Nuclear Energy System Assessment (NESA) scenario — was established during IAEA experts mission in Romania in the framework of the NESA in Romania using INPRO methodology national project, following the ISPE suggestions.

The nuclear fuel cycle in Romania is a once through open fuel cycle, characteristic for CANDU reactors. In the model for the considered time horizon (2050), no changes were assumed in the option for the nuclear fuel cycle and also in national legislation regarding the decision to not support the activities for nuclear fuel enrichment and/or reprocessing. The nuclear fuel for existing CANDU reactors is fabricated by the Piteşti Nuclear Fuel Plant (qualified by AECL as a CANDU fuel supplier), based on domestic uranium reserves, the same path being used also for the fuel needed for CANDU Units 3 and 4 operation. The fresh fuel needed for advanced PWRs or PHWRs operation is assured by imports of already fabricated fuel assemblies.

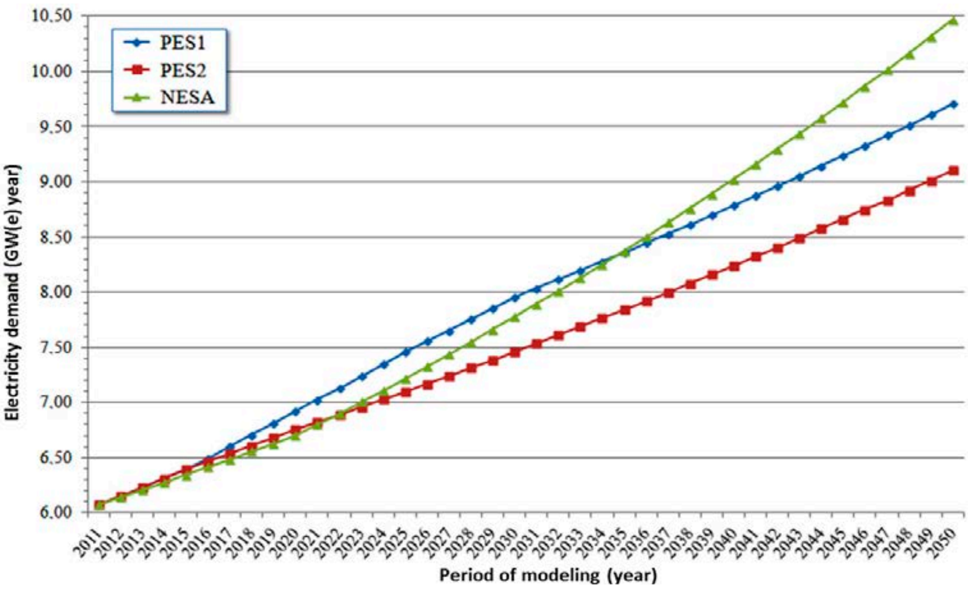


FIG. 3.44. Electricity demand scenarios considered.

[8] See the Energy Roadmap for Romania (Decision No. 890/2003), the Strategy for Using Renewable Energy Sources, (Decision No. 1535/2003) and the National Renewable Energy Action Plan: Romania.

The spent fuel discharged from the reactors is cooled down first in the nuclear power plant spent fuel bay (five years for advanced PWRs and six years for HWRs), then the intermediate wet cooling continues with the intermediate dry storage (50 years for CANDU reactors and advanced HWRs). The corresponding facilities being built on nuclear power plants site; for the advanced PWR, spent fuel will be stored into a regional storage facility, with corresponding associated costs, as a service.

A detailed description of all input data considered for the analysis is presented in Annex V on the CD-ROM accompanying this publication. In order to perform the Romanian energy system modelling, the IAEA MESSAGE code was used (see Ref. [3.36]). For each electricity demand evolution scenario, different discount rates (5%, 8% and 10%) were considered and separate runs were performed for each case.

An economic analysis was also performed to evaluate the nuclear energy cost competitiveness against alternative energy sources. The final goal is to search solid arguments sustaining the nuclear power plants comparatively with the classical fossil fuel plants, highlighted by the evolution of specific economic indicators (LUEC, internal rate of return, IRR, return on investment, ROI, net present value, NPV, total investment/investments limit). Both for nuclear and classic non-nuclear technologies advanced solutions have been considered. Calculation of the mentioned economic parameters were performed with the Nuclear Economics Support Tool (NEST) code, based on the formula provided in Ref. [3.37]. In the comparative economic study, three types of technology were:

— Nuclear power plant (advanced PWR and advanced PHWR);
— Coal fired power plant (power plant using lignite fossil fuel, with carbon capture);
— Gas fired power plant (power plant operating on combined cycle, with carbon capture).

The electricity generation costs calculated are plant level costs, at the station and do not include transmission and distribution costs. For the initial capital investment, the uniform investment schedule has been used for all the considered energy sources. A detailed description of all input data considered for the economic analysis is also presented in Annex V.

3.1.8.4. Summary presentation and analysis of the results

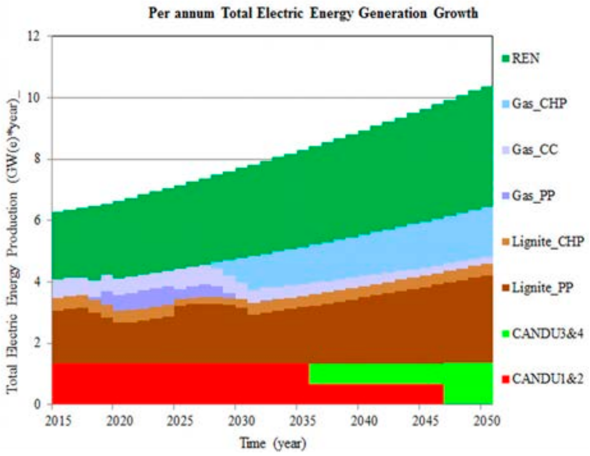
The parameters of interest (and their evolution during the modelling period until the considered time horizon) for the present study were, as follows:

— Annual total electric generation growth (GW(e)·year) and percentage share;
— Annual total installed capacity growth, GW(e) and percentage share;
— Annual nuclear electric generation growth, GW(e)·year;
— Nuclear new installed capacities, GW(e);
— Investments in new nuclear power plants, US $billion;
— Cumulative uranium consumption, kt HM;
— Annual uranium requirements, kt HM/year;
— Annual fuel requirements, kt HM/year;
— Annual discharged spent fuel (spent fuel in interim wet storages), kt HM/year;
— Spent fuel in interim dry storages, kt HM/year.

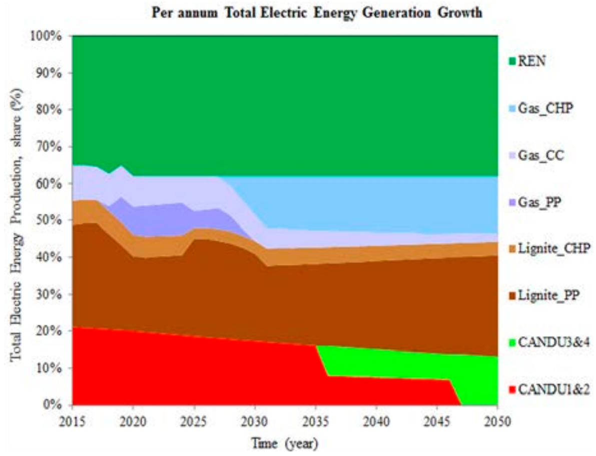
Taking into consideration only the annual discount rate of 8% (this rate being, as mentioned before, the most appropriate for Romania's conditions and economic and financial environment), the results obtained for the three considered NES development scenarios are presented in the following.

(a) NESA Basic scenario: Case study reference scenario

The annual total electric energy generation and the nuclear electric energy production growth, the annual total installed capacity growth for considered the Romanian energy mix, the new installed nuclear capacity and corresponding investment evolution are presented in Figs 3.45–3.49. In Figs 3.50 and 3.51, the annual uranium requirements and the corresponding cumulative consumption are represented. The fresh fuel requirements are illustrated in Fig. 3.52, and Fig. 3.53 presents the cumulative volume of spent fuel in interim dry storage.

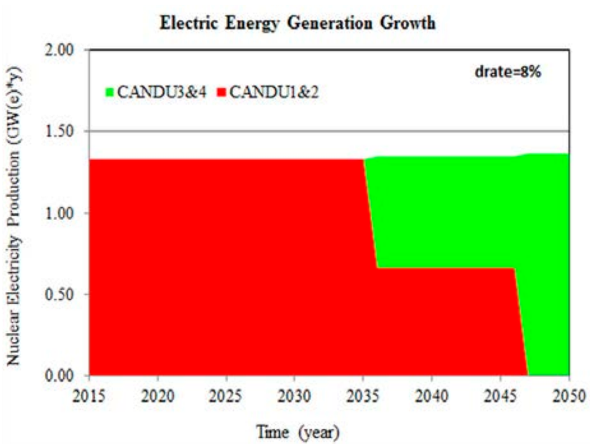


(a) Unit 1

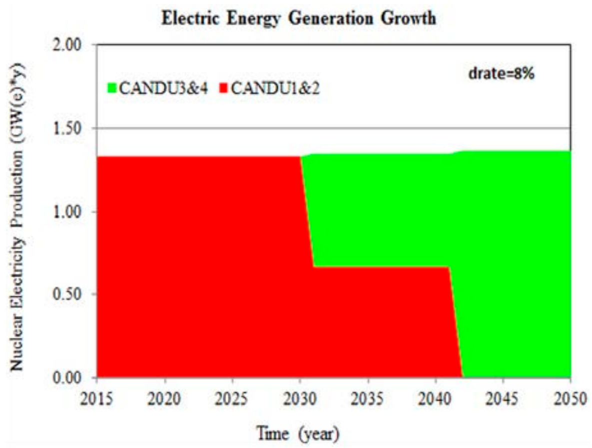


(b) Unit 2

FIG. 3.45. Annual total electric energy generation growth, GW(e)·year, and % share, NESA Basic scenario, 8% discount rate, 40 year lifetime for CANDU.

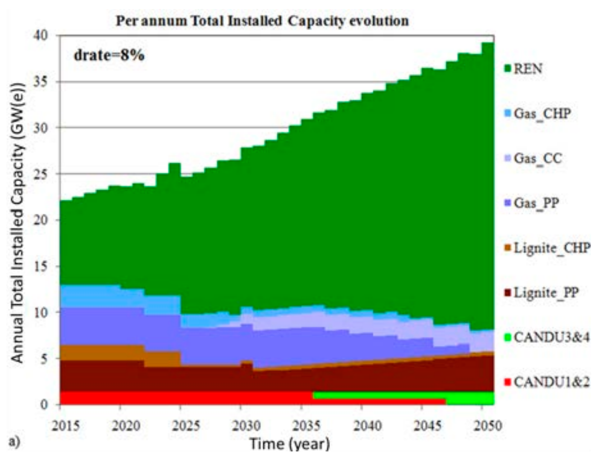


(a) 40 years

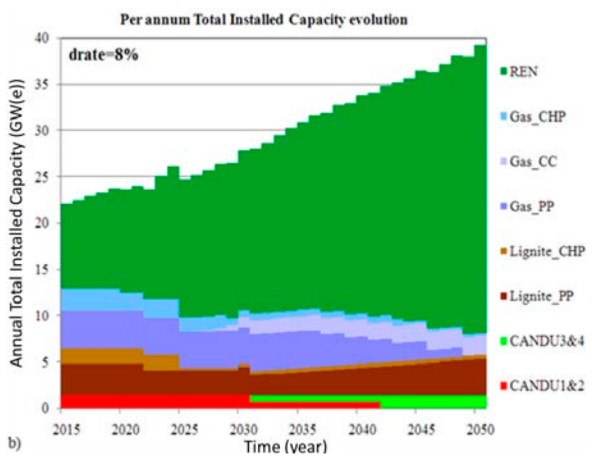


(b) 35 years

FIG. 3.46. Annual nuclear electricity production, GW(e)·year, NESA Basic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.

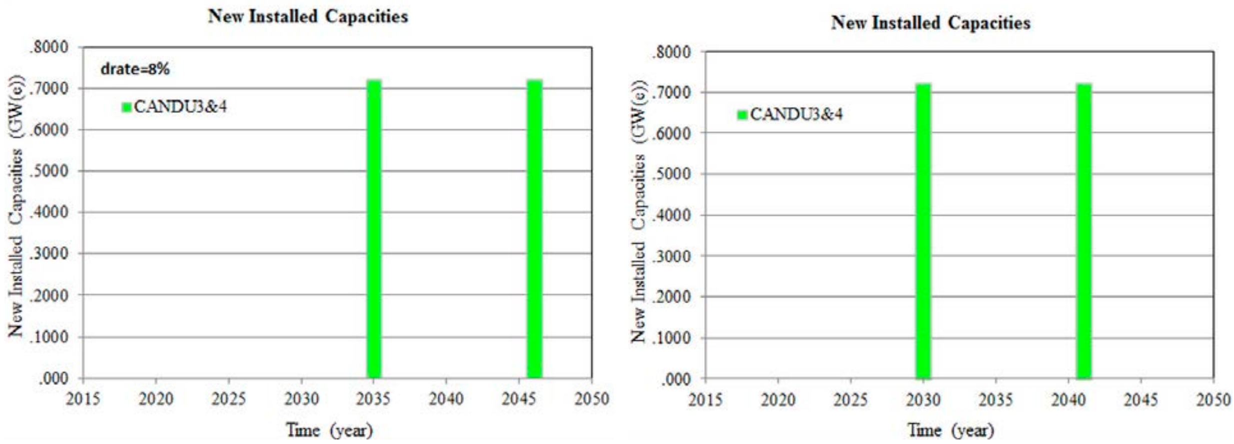


(a) 40 years



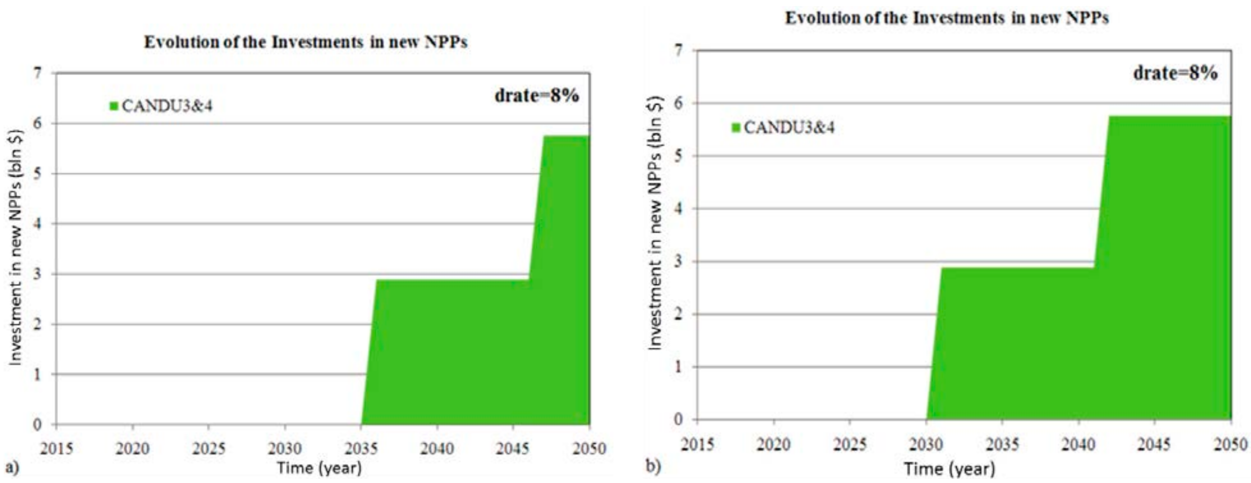
(b) 35 years

FIG. 3.47. Annual total installed capacity growth, GW(e), NESA Basic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.



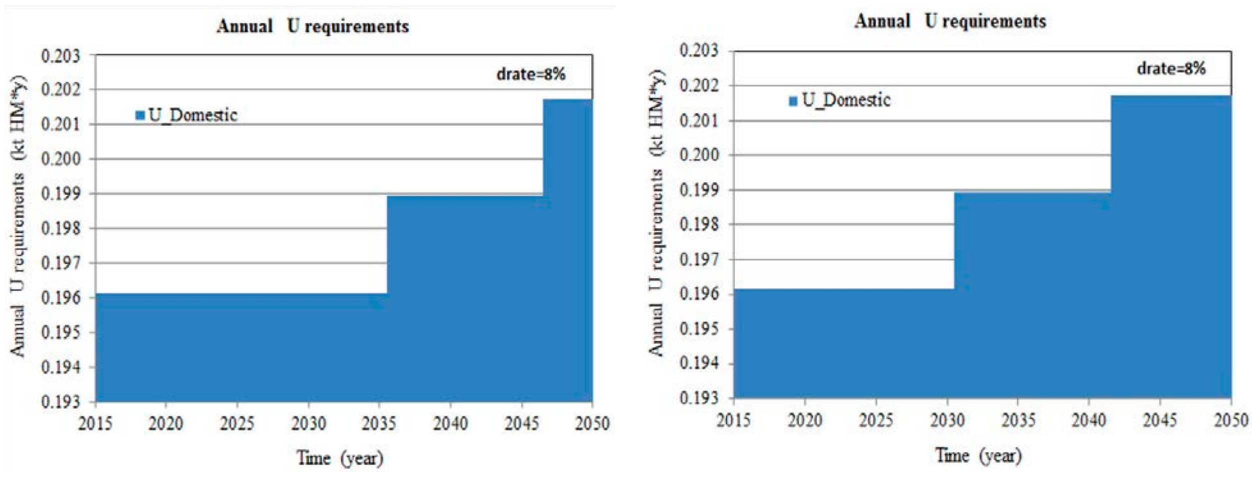
(a) 40 years (b) 35 years

FIG. 3.48. New installed nuclear capacities, GW(e), NESA Basic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.



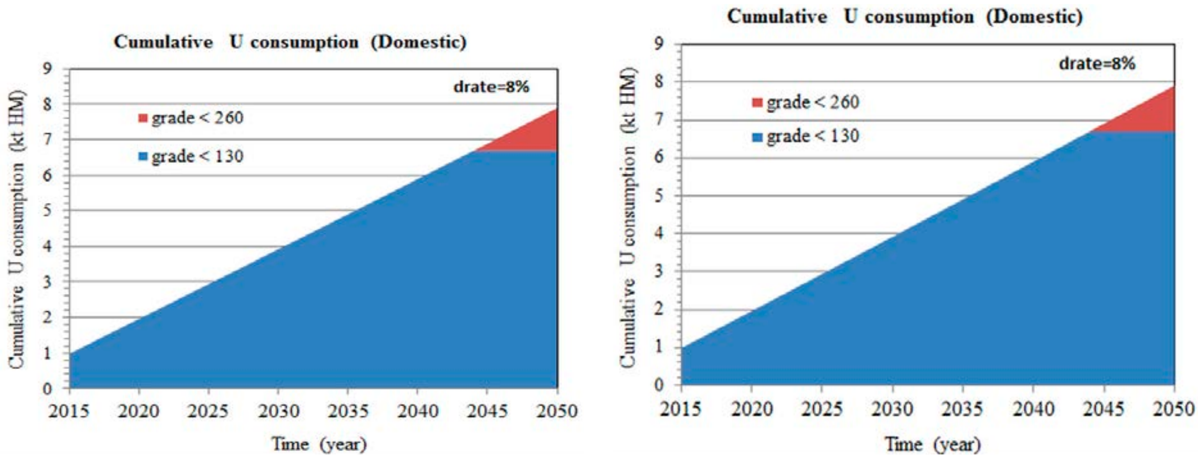
(a) 40 years (b) 35 years

FIG. 3.49. Investments in nuclear energy capacities, US $billion, NESA Basic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.



(a) 40 years (b) 35 years

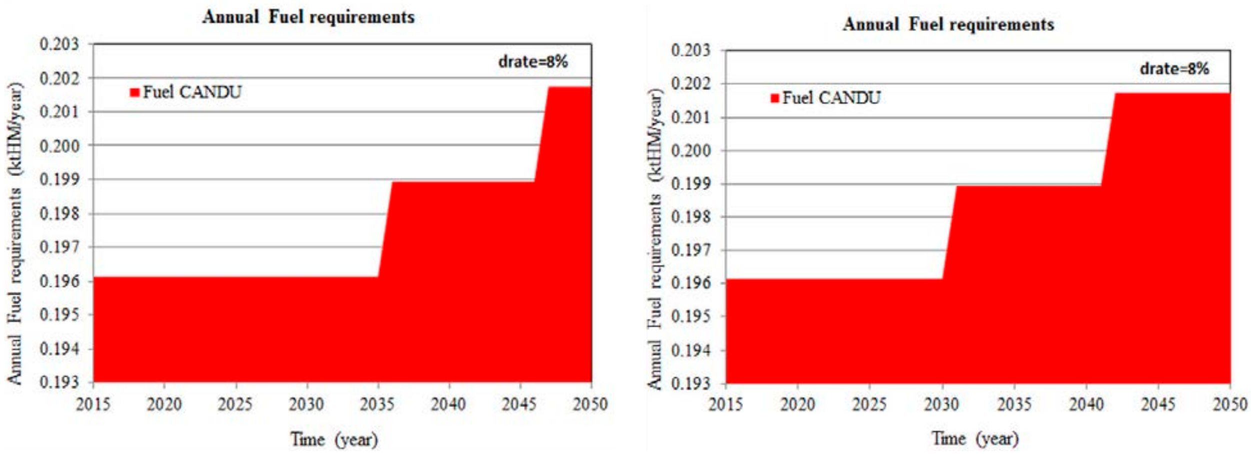
FIG. 3.50. Annual uranium requirements, kt HM/year, NESA Basic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.



(a) 40 years

(b) 35 years

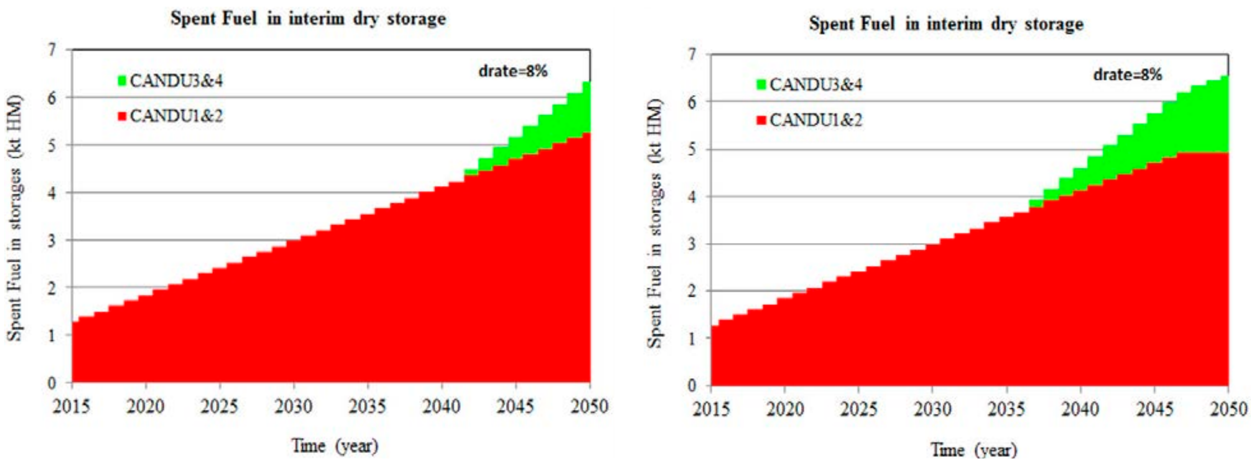
FIG. 3.51. Cumulative uranium consumption, kt HM, NESA Basic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.



(a) 40 years

(b) 35 years

FIG. 3.52. Fresh fuel annual requirements, kt HM/year, NESA Basic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.



(a) 40 years

(b) 35 years

FIG. 3.53. Cumulative spent fuel in storages, t HM, NESA Basic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.

The construction of CANDU Units 3 and 4 will be brought forward (both units commissioned before 2030) if the annual discount rate is 5%; for an annual discount rate of 10%, only one new CANDU unit will be constructed, after 2040. Considering an annual discount rate of 5%, the cumulative uranium consumption will reach about 11 kt HM for 40 years of operation for CANDU Units 1 and 2 and about 9 kt HM for 35 years. For a discount rate of 10%, the cumulative uranium consumption will be about 8 kt HM for 40 years of operation for CANDU Units 1 and 2, and around 6 kt HM for 35 years. It has to be mentioned here that domestic RAR are estimated at only 7 kt HM.

In the case of pessimistic scenarios (Pes1 and Pes2) for the demand evolution, the results are similar and show that for all the discount rates considered in the study, both Units 3 and 4 from the Cernavodă nuclear power plant are still under consideration to be built, except for the case of 10% discount rate and short lifetime of CANDU Units 1 and 2 when only one new CANDU reactor is added after 2040.

In the reference scenario (NESA Basic scenario) for nuclear energy development, with an annual discount rate of 8%, the following is concluded:

- The annual electric energy produced by the nuclear capacities assures about 1.3 GW(e) by operation of two CANDU reactors (Units 1 and 2 until 2030 or 2035, Units 2 and 3 until 2041 or 2046 and Units 3 and 4 there after). The nuclear energy share in the Romanian energy mix decreases from 22% to 14% in 2050.
- At the end of 2050, the cumulative consumption of uranium was estimated to about 8 kt U (larger than domestic RAR+IR, about 1.2 kt HM being assured from the prognosticated and speculative resources), the annual uranium requirements being 0.2 kt HM. It can be taken into account to use uranium or uranium technical concentrates or even uranium fresh fuel from import, if these solutions are sustained by the economical advantages.
- The volume of spent fuel in interim dry storage was estimated at 6.33–6.55 kt HM, from which about 5 kt HM is spent fuel produced by the operation of CANDU Units 1 and 2.

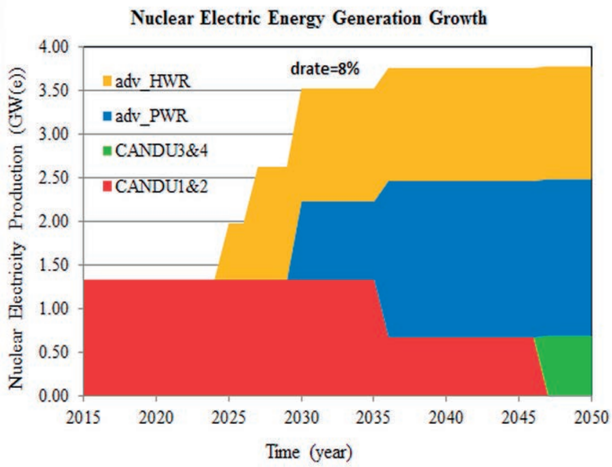
(b) NESA Optimistic scenario

For the optimistic scenario, two options for the addition of new advanced PWR/HWR (bound and no bound) were into account in the following. The annual nuclear electric energy production growth is presented in Fig. 3.54. Figures 3.55 and 3.56 present the new installed nuclear capacities and the corresponding investment evolution. In Figs 3.57 and 3.58, the annual uranium requirements and the corresponding cumulative uranium consumption are represented. The fresh fuel requirements are illustrated in Fig. 3.59, and Fig. 3.60 presents the cumulative volume of spent fuel in interim dry storage.

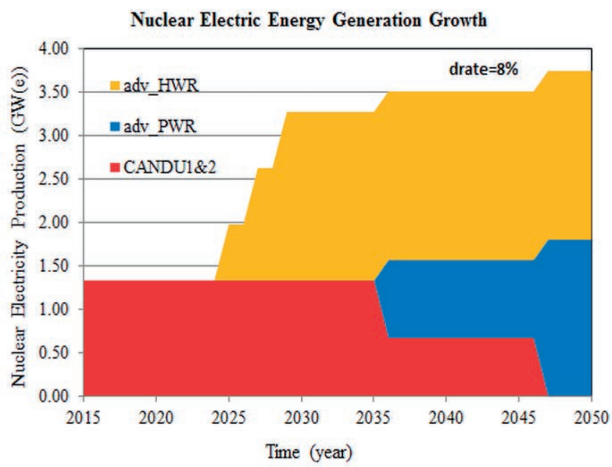
In the case of pessimistic scenarios (Pes1 and Pes2) for the demand evolution, the results are similar and show that both Units 3 and 4 from the Cernavodă nuclear power plant are only under consideration to be built at a discount rate of 5%; at 8% only one CANDU reactor will be built; and at 10% no new CANDU reactor will be built.

In the NESA Optimistic scenario for NES development bound on the commissioning of advanced PWR and/or advanced HWR (after 2035), the following is concluded:

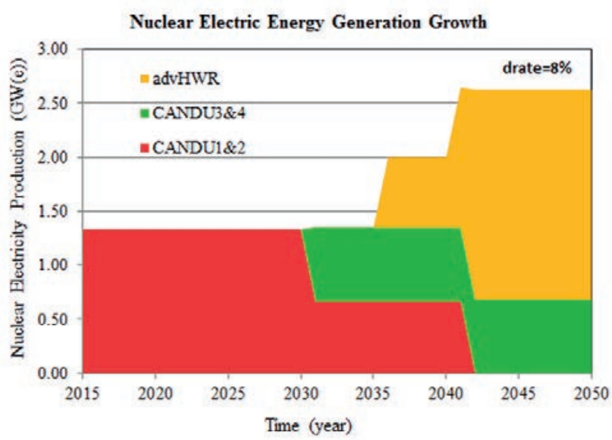
- The annual nuclear electricity production can reach up to 2.6 GW(e): commissioning of only CANDU Unit 3 in 2030 and another three advanced HWRs in 2035–2045; CANDU Unit 4 construction is delayed after 2050 due to economic reasons. The nuclear share in the Romanian energy mix reaches 30%.
- The cumulative uranium consumption was estimated to be about 6.7 kt, without exceeding the existing RAR+IR. It has to be mentioned here that the study assumption was to assure from import the fresh fuel needed for advanced HWR operation in order to respect the national regulations regarding the interdiction of uranium enrichment and spent fuel reprocessing activities. The annual fuel requirements were estimated at 0.4 kt HM, from which about 0.2 kt HM are used for CANDU reactor operation.
- The volume of spent fuel in interim dry storage reaches about 7.5 kt HM, from which about 5 kt HM is spent fuel produced by CANDU reactor operation.



(a) Bound

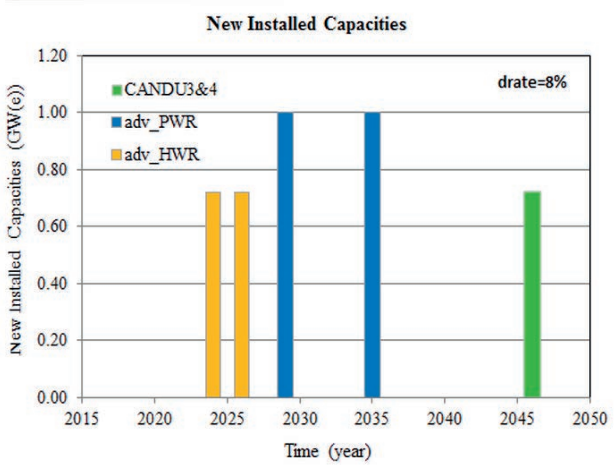


(b) No bound on advanced PWR/HWR addition

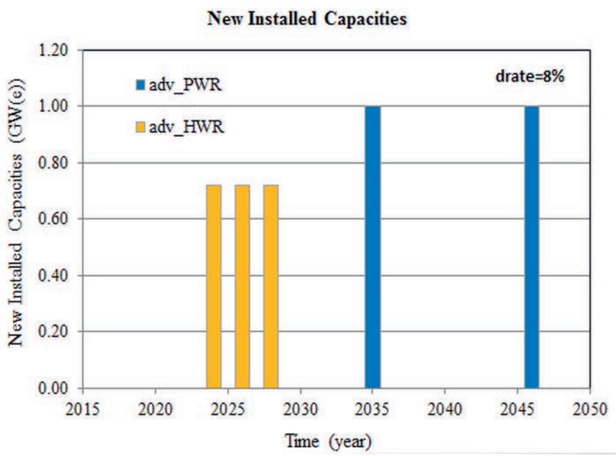


(c) 35 year lifetime CANDU Units 1 and 2

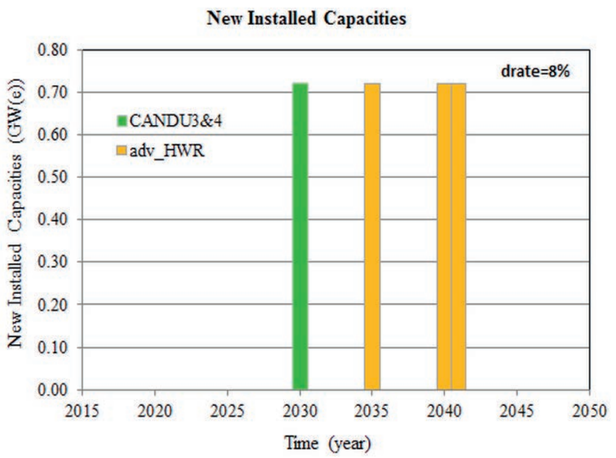
FIG. 3.54. Annual nuclear electricity production, GW(e)·year, NESA Optimistic scenario, 8% discount rate, 40 year lifetime for CANDU Units 1 and 2.



(a) Bound

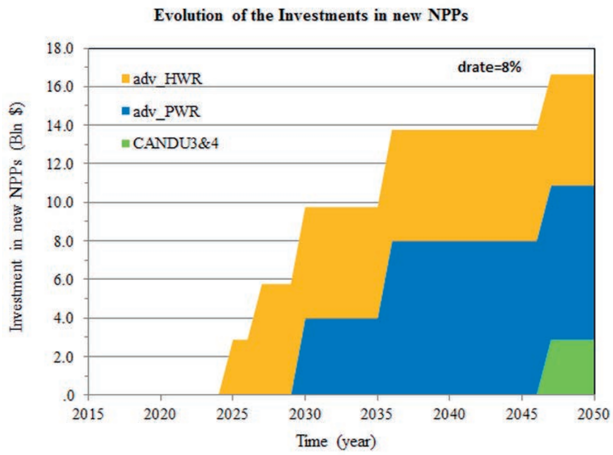


(b) No bound on advanced PWR/HWR addition

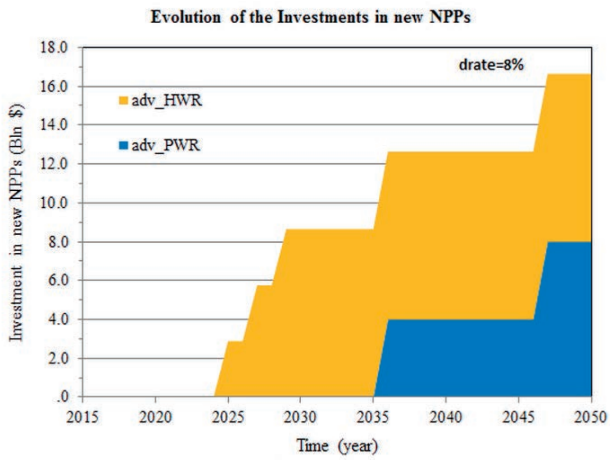


(c) 35 year lifetime CANDU Units 1 and 2

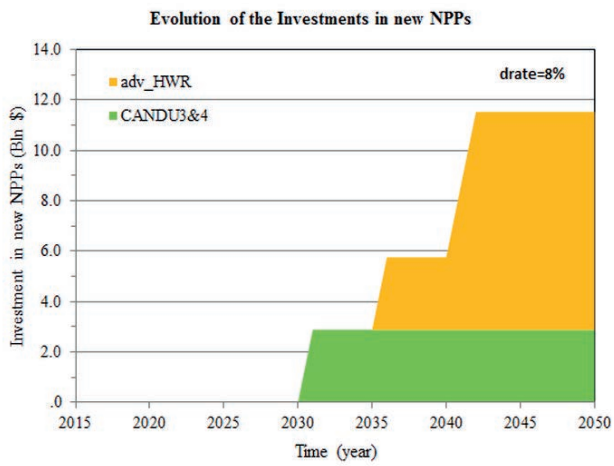
FIG. 3.55. New installed nuclear capacities, GW(e), NESA Optimistic scenario, 8% discount rate, 40 year lifetime for CANDU Units 1 and 2.



(a) Bound

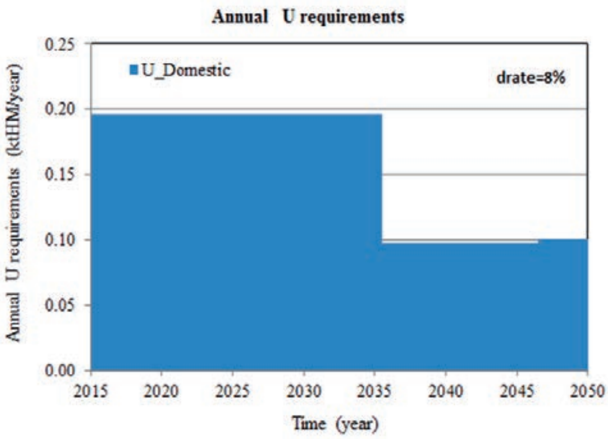


(b) No bound on advanced PWR/HWR addition

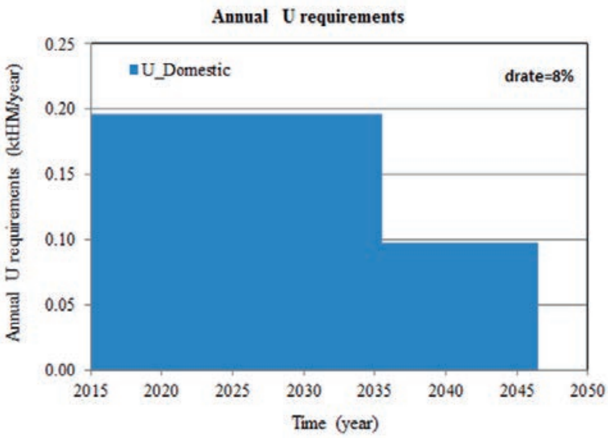


(c) 35 year lifetime CANDU Units 1 and 2

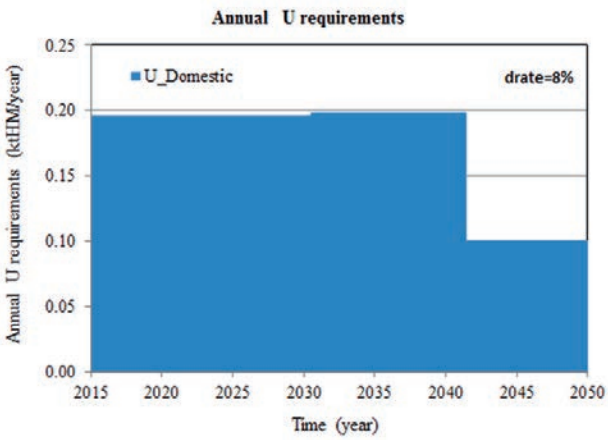
FIG. 3.56. Investments in nuclear energy capacities, US $billion, NESA Optimistic scenario, 8% discount rate, 40 year lifetime for CANDU Units 1 and 2.



(a) Bound

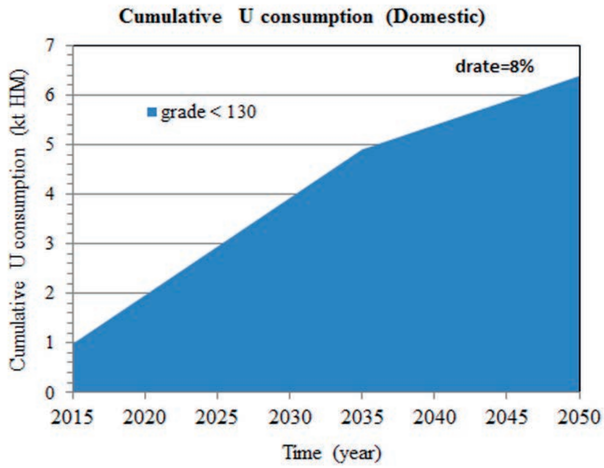


(b) No bound on advanced PWR/HWR addition

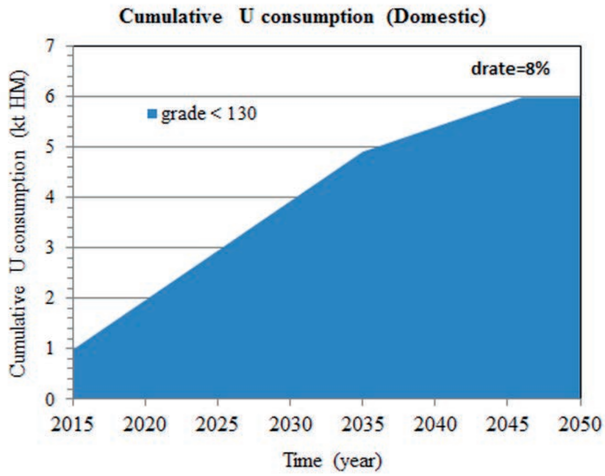


(c) 35 year lifetime CANDU Units 1 and 2

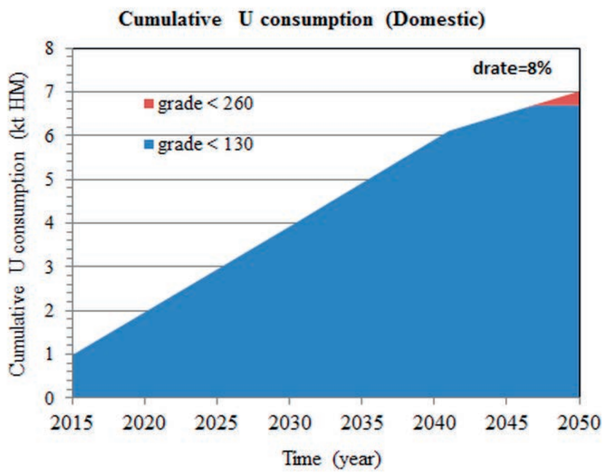
FIG. 3.57. Annual uranium requirements, kt HM/year, NESA Optimistic scenario, 8% discount rate, 40 year lifetime for CANDU Units 1 and 2.



(a) Bound

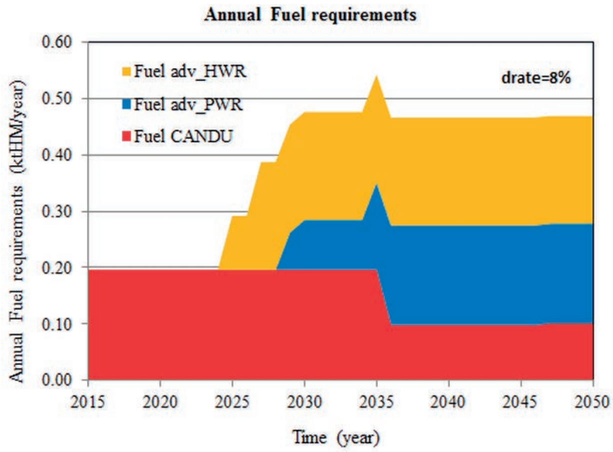


(b) No bound on advanced PWR/HWR addition

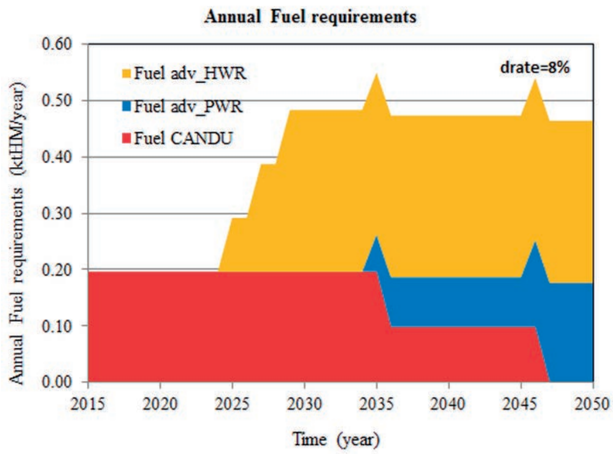


(c) 35 year lifetime CANDU Units 1 and 2

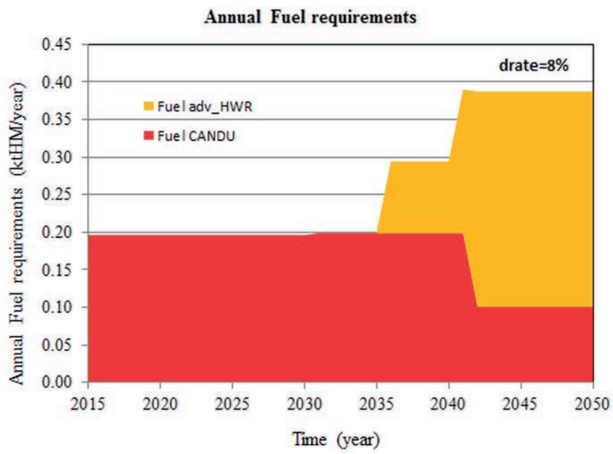
FIG. 3.58. Cumulative uranium consumption, kt HM, NESA Optimistic scenario, 8% discount rate, 40 year lifetime for CANDU Units 1 and 2.



(a) Bound

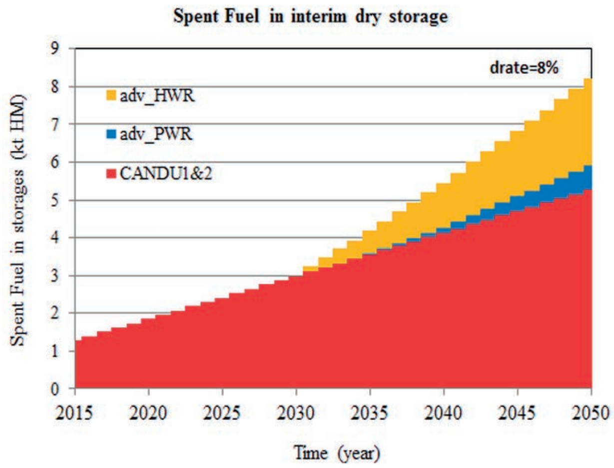


(b) No bound on advanced PWR/HWR addition

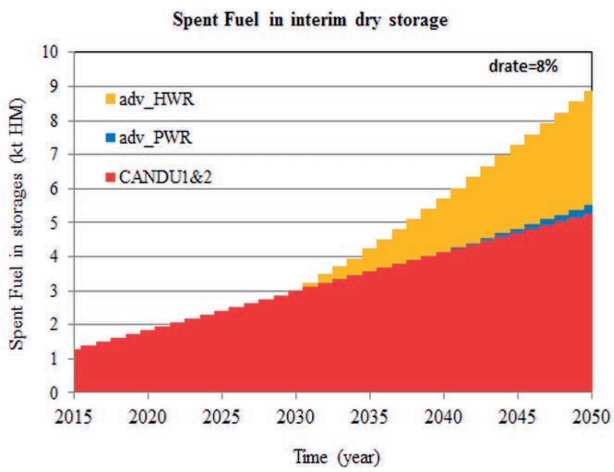


(c) 35 year lifetime CANDU Units 1 and 2

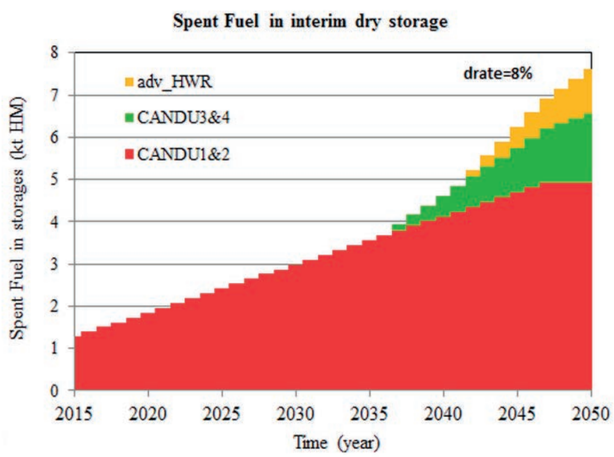
FIG. 3.59. Fresh fuel annual requirements, kt HM/year, NESA Optimistic scenario, 8% discount rate, 40 year lifetime for CANDU Units 1 and 2.



(a) Bound



(b) No bound on advanced PWR/HWR addition



(c) 35 year lifetime CANDU Units 1 and 2

FIG. 3.60. Cumulative spent fuel in storages, kt HM, NESA Optimistic scenario, 8% discount rate, 40 year lifetime for CANDU Units 1 and 2.

In the NESA Optimistic scenario for NES development with no bound on the commissioning of advanced PWR and/or advanced HWR (after 2035), the following is concluded:

— The annual nuclear electricity production reaches up to 3.8 GW(e) after 2035: two advanced HWRs (until 2025) and two advanced PWRs (after 2025) and only CANDU Unit 3 (after 2045); CANDU Unit 4 construction is delayed after 2050 due to economic reasons. The nuclear share in the Romanian energy mix can reach about 45%.
— The cumulative uranium consumption was estimated to be about 6.7 kt, without exceeding the existing RAR+IR. The fresh fuel needed for advanced PWR and advanced HWR operation is assured from import, with respect to national regulations regarding the interdiction of uranium enrichment and spent fuel reprocessing activities. The annual fuel requirements were estimated at 0.5 kt HM, from which about 0.1 kt HM are used for CANDU reactor operation.
— The volume of spent fuel in interim dry storage reaches about 8 kt HM, from which about 5 kt HM is spent fuel produced by CANDU reactors operation. It should be mentioned that the study assumed that the spent fuel from advanced PWR will be stored outside the country in a regional storage facility.

(c) NESA Pessimistic scenario

In the following, the results obtained for the NESA Pessimistic scenario are presented, considering the NESA energy demand evolution scenario, 8% discount rate and two options for the operating CANDU Units 1 and 2, Cernavodă nuclear power plant (35 and 40 years). The annual nuclear electric energy production growth is presented in Fig. 3.61. In Figs 3.62 and 3.63, the annual uranium requirements and the corresponding cumulative uranium consumption are represented. The fresh fuel requirements are illustrated in Fig. 3.64. Figure 3.65 presents the cumulative volume of spent fuel in interim dry storage.

Considering the pessimistic energy demand scenarios, the results were similar with the NESA scenario, in the study being observed that Pes1 and Pes2 scenario influence is noticed for nuclear development in the considered Basic and Optimistic Scenarios. For the NES-Pessimistic scenario, the following is concluded:

— The annual nuclear electric energy production is about 1.3 GW(e) (with both CANDU Units 1 and 2 in operation), reduces to 0.6 GW(e) after 2030 or 2035 (shutdown of CANDU Unit 1), and there is no nuclear electricity produced after 2040 or 2045 (shutdown of CANDU Unit 2). The national electricity demand in the Romanian energy mix has to be assured by increasing the share of renewable capacites or building classic thermal capacities with improved technologies for preserving the low CO2 emissions required level.
— The cumulative uranium resources consumption was estimated at about 6 kt, this amount being assured by the estimated domestic RAR+IR.
— The volume of spent fuel in interim dry storage reaches 5.26 kt HM.

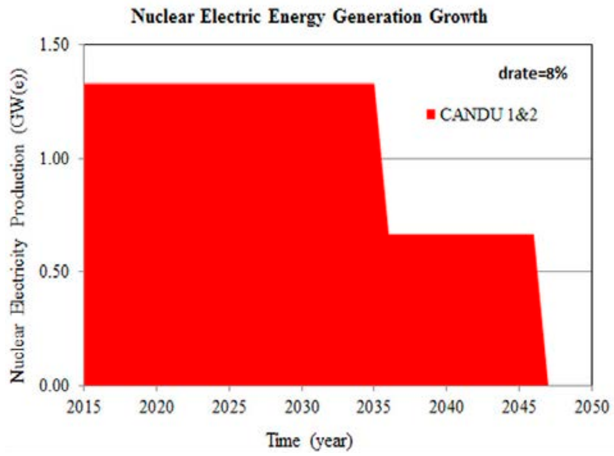
(d) The economic analysis for a nuclear energy cost competitiveness assessment

The economic analysis was performed to evaluate the nuclear energy cost competitiveness against alternative energy sources. The study final goal proposes to search solid arguments sustaining nuclear power plants comparatively with classical fossil fuel plants, highlighted by the evolution of specific economic indicators (LUEC, IRR, ROI, NPV and total investment/investments limit).

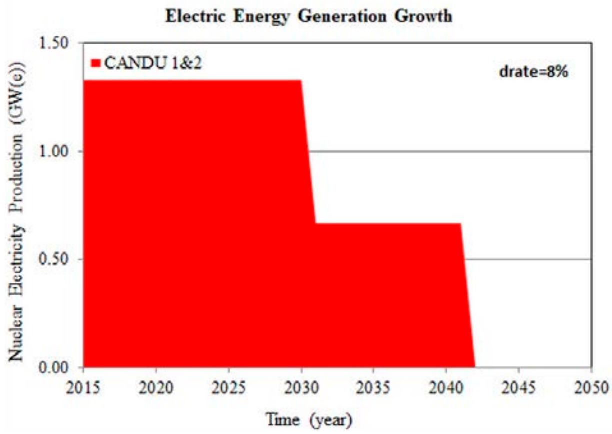
Advanced solutions were considered for both nuclear and classic non-nuclear technologies. Three types of technology were considered: nuclear power plant (advanced PWR and advanced PHWR), coal fired power plant (power plant using lignite fossil fuel, with carbon capture) and gas fired power plant (power plant operating on combined cycle, with carbon capture).

For the comparative economic study, the input parameters values (country specific economic parameters, power plant specific technical and economic parameters, and nuclear power plant additional specific technical parameters) were collected [3.4, 3.11, 3.38–3.43][9] and were used as initial input values for the NEST code calculations [3.37]. For the initial capital investment the uniform investment schedule has been used for all

[9] See also the National Institute of Statistics, Romania, at www.insse.ro

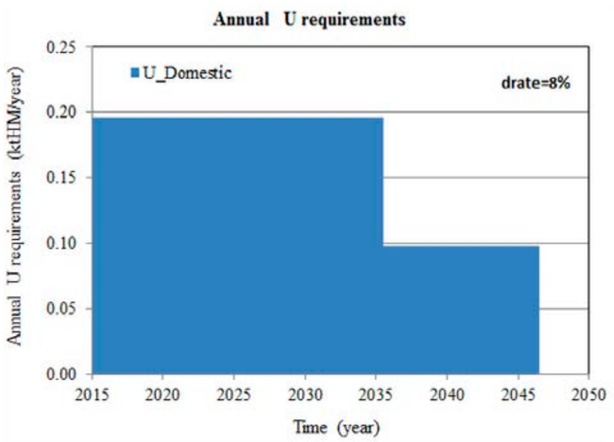


(a) 40 years

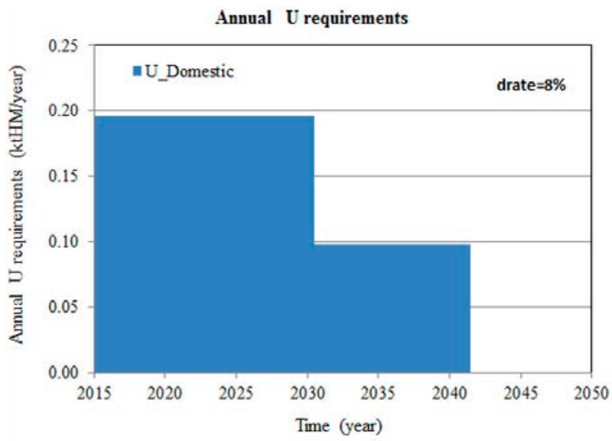


(b) 35 years

FIG. 3.61. Annual nuclear electricity production, GW(e)·year, NESA Pessimistic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.

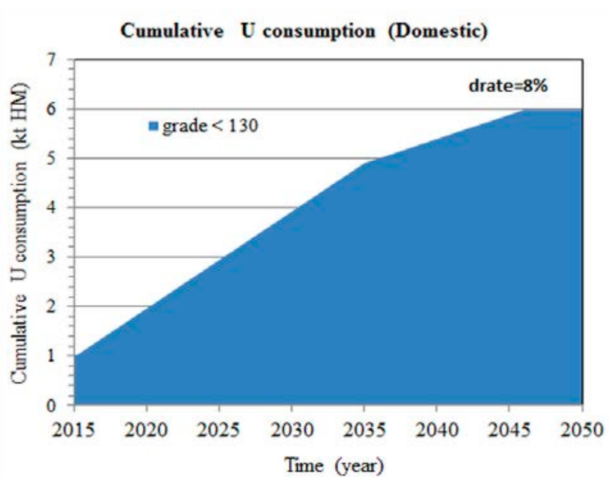


(a) 40 years

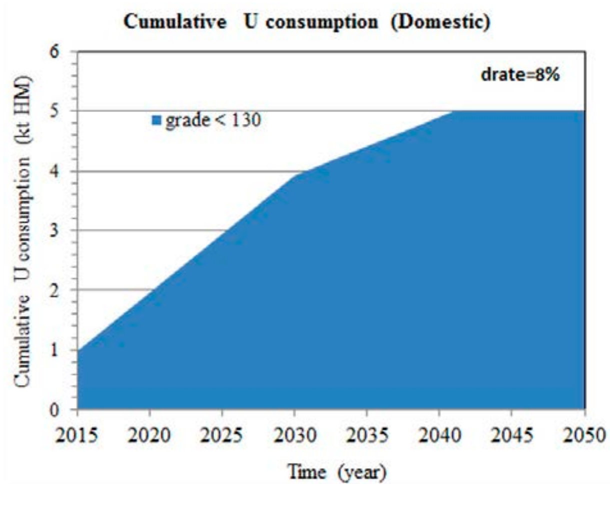


(b) 35 years

FIG. 3.62. Annual uranium requirements, kt HM/year, NESA Pessimistic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.

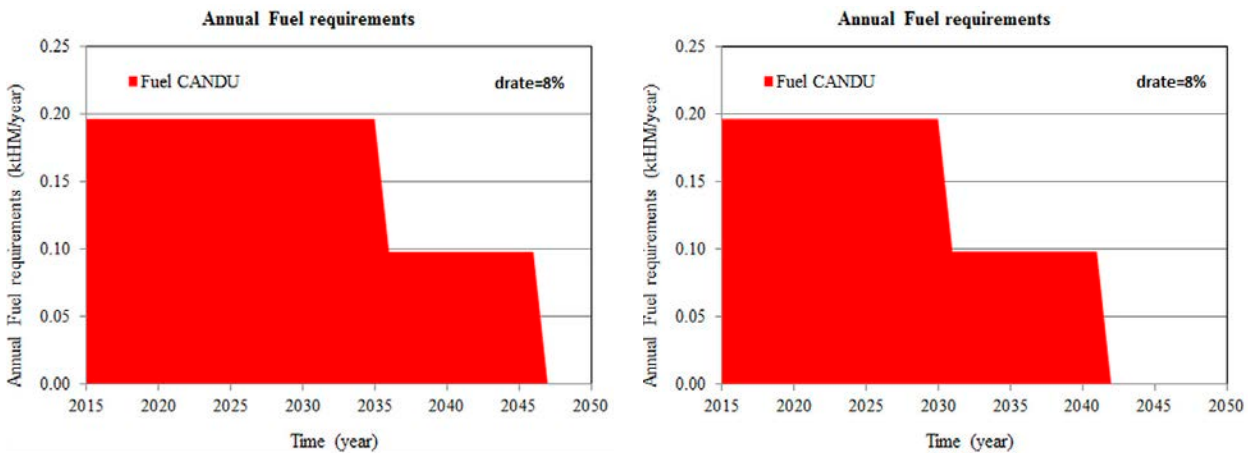


(a) 40 years



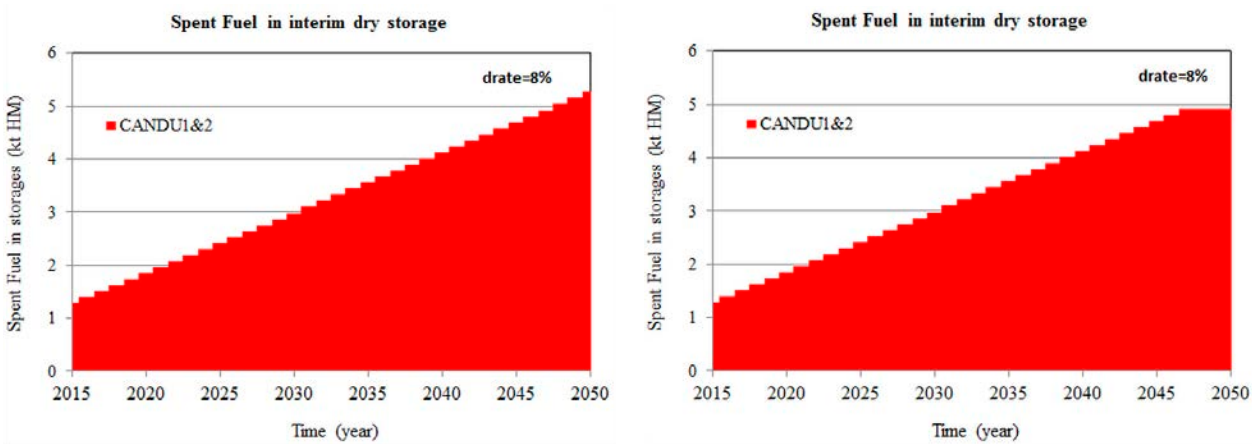
(b) 35 years

FIG. 3.63. Cumulative uranium consumption, kt HM, NESA Pessimistic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.



(a) 40 years (b) 35 years

FIG. 3.64. Fresh fuel requirements, kt HM/year, NESA Pessimistic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.



(a) 40 years (b) 35 years

FIG. 3.65. Spent fuel in interim dry storage, kt HM, NESA Pessimistic scenario, 8% discount rate, lifetime for CANDU Units 1 and 2.

the considered energy sources. Economic analyses were performed considering 8% annual discount rate as representative for Romania.

The advanced HWR is the best economic option with a LUEC value of US $38.14 × 10^{-3}/kW·h, for the initial data. The advanced PWR follows with around a 20% higher LUEC value of US $46.52 × 10^{-3}/kW·h, the coal fired power plant with around a 37% higher LUEC value of US $63.09 × 10^{-3}/MW·h and gas fired power plant with around a 50% higher LUEC value of US $71.33 × 10^{-3}/MW·h. The advanced HWR LUEC is taken as the reference value for the comparison.

The electricity produced by nuclear power plants is cost competitive against coal and gas fired power plant electricity. IRR values for the considered competing technologies were almost equal, the lowest IRR value of 0.13 for advanced PWR; 0.15 was obtained for both advanced HWR and the coal fired power plant — very small differences compared to the leader. ROI values for nuclear power plants were better than those for classic technologies, the leader being this time the advanced HWR at 0.46, against the advanced PWR at 0.39. NPV values for the nuclear technologies were higher than those for the alternative classic technologies.

In conclusion, for all the considered figures of merit (IRR, ROI and NPV), nuclear technology was proven to be more attractive for investors than the fossil fuel classic technology improved to reduce greenhouse gas emissions.

The sensitivity analysis was performed for the defined alternate technologies considering the variation of discount rate, fixed operation and maintenance costs, overnight costs, load factor, lifetime, construction time and investment schedule. For all considered parameters, the highest impact was obtained for capital intensive technologies, the advanced PWR and the advanced HWR, the lowest impact being obtained for the gas fired power plant. In most of the sensitivity cases, the lowest LUEC value was obtained for the advanced HWR.

The variation of annual discount rate has the highest impact on LUEC. Considering as reference the initially assumed discount rate (10% per year), the impact of variation of discount rate on calculated LUEC was, as follows: for a discount rate of 5% per year, LUEC characterizing the nuclear technologies was 90–95% smaller, for the coal fired power plant 14% smaller, and for the gas fired power plant 0.6% smaller than LUEC reference value; for a discount rate of 15% per year, LUEC characterizing the nuclear technologies was 70% greater, for the coal fired power plant 18% greater; and LUEC for the gas fired power plant 0.8% greater than LUEC reference value.

The lowest impact on LUEC is due to power plant lifetime variation, the difference in calculated LUEC for nuclear technologies being less than 3% for a discount rate of 5% per year, less than 0.5% for a discount rate of 10% per year, and less than 0.01% for a discount rate of 15% per year.

3.1.8.5. Conclusions

The study proved that nuclear energy is an important candidate for the national production of electricity, in conditions of cost competitiveness, safety and security of supply. In order to assure the projected national electricity demand, the nuclear energy share in the national energy mix can be increased from the present value (about 20% from the total production of electric energy) according to the strategic documents in force.

The considered scenarios for the nuclear energy development shown that the amount of uranium needed for the nuclear capacities operation can be assured from the RAR+IR domestic resources in the NESA Basic and Pessimistic scenario conditions for an 8% annual discount rate. For the same discount rate in the NESA Optimistic scenario conditions, additional amounts of uranium are needed, these quantities being assured from the prognosticated and speculative domestic resources or by the import of uranium, uranium technical concentrates or fresh fuel.

The spent fuel discharged from the reactors is cooled down first in the intermediate wet spent fuel bay inside the nuclear power plant (five years for the advanced PWR and six years for HWRs), then the cooling period continues with the intermediate dry storage (50 years for CANDU reactors and advanced HWRs), the corresponding facilities being built on nuclear power plants site. For the advanced PWR, spent fuel will be stored into a regional storage facility, with corresponding associated costs.

In the NESA Basic scenario, the volume of spent fuel in interim dry storage was estimated at 6.33–6.55 kt HM, from which about 5 kt HM is spent fuel produced by the operation of CANDU Units 1 and 2. In the NESA Optimistic scenario, the volume of spent fuel in interim dry storage reaches about 7.5–8 kt HM, from which about 5 kt HM is spent fuel produced by the CANDU reactors operation. It should be mentioned that the study assumed that the spent fuel from the advanced PWR will be stored outside the country in a regional storage facility. For NESA Pessimistic scenario conditions, the spent fuel volume in interim dry storage reaches 5.26 kt HM.

The construction of nuclear capacities will be brought forward for a smaller discount rate. As the discount rate value increases, the investment for nuclear capacities (capital intensive technologies) are larger and spread on a longer period of time, so the nuclear capacities construction will be delayed.

The economic analysis on the competitiveness of nuclear energy against alternative electricity sources is considered useful in providing substantial technical support for the decision making regarding a comprehensive and responsible national nuclear energy strategy on medium term envisaging the transition to long term globally sustainable NES. The present study integrates the SYNERGIES objective by offering a global vision of the Romanian national resources and capabilities, including nuclear energy capacity development, in the medium and long term, in order to address in the future collaboration options for energy sustainability in regional and global context. The complete presentation of the case study conclusions is provided in Annex V.

3.1.9. Scenarios with replacement heat generation

3.1.9.1. Introduction

Research work was performed on possible future development of nuclear energy generation in Ukraine. The study was implemented under Task 2 of the IAEA SYNERGIES project, including research on the possibility of wide deployment of nuclear reactors for non-electricity use (heat production) and assessment of nuclear energy development based on Generation IV reactors. Proposals were made for international cooperation in the development of NESs in the medium and long term using Generation III+ and IV reactors. Neither of these scenarios were considered during the GAINS collaborative project (see Appendix III). The complete case study can be found in Annex XXII on the CD-ROM accompanying this publication.

3.1.9.2. Objective and problem formulation

The future deployment of nuclear power in Ukraine has to take into consideration the high cost of nuclear fuel cycle options and the low cost of non-nuclear electricity generation. Current power generation is largely based on coal and gas consumption, which produces CO_2 emissions. Economic development of Ukraine is likely to increase overall CO_2 emissions. In this context, Ukraine is considering wide deployment of nuclear power as a means to limit CO_2 emissions as well as to strengthen the security of energy supply and decrease the costs of national electricity generation.

Nuclear infrastructure in Ukraine is based on open fuel cycle options, which produce a significant amount of spent nuclear fuel. Reprocessing facilities are not widely in use, and their high cost suggests there will be no such facilities in Ukraine for the foreseeable future. Moreover, the high capital cost of nuclear power generation is largely responsible for decreasing development of nuclear reactors based on Generation III and III+ technologies. The significant improvement of the technical and economical parameters of innovative nuclear reactors shall be considered as a means to enhance the economic attractiveness of electricity production by nuclear generation in Ukraine.

3.1.9.3. Assumptions, methods, codes and input data used

(a) General assumptions

The energy system of Ukraine is modelled by generation forms independent of specific power units and regional features. Nuclear generation, however, is represented by different reactor types: LWRs installed, advanced LWRs, and small modular reactors (SMRs) for Scenario 1; and LWRs installed, advanced LWRs and SCWRs for Scenario 2. Economic parameters (e.g. price for resources and capital construction) are given in short term prices (overnight cost).

The modelling of non-nuclear-generated energy is performed using the following boundary conditions:

— Solar power plants and bioenergy have a small contribution to electricity production.
— Coal reserves are enough to cover energy needs in full scope and thus are considered to be unlimited. The mining rate is also unlimited.
— Gas for energy generation is imported, therefore its reserves are assumed to be unlimited.
— Electric power losses in the grids are decreased in accordance with the updated Energy Strategy until 2030[10], and then they remain unchanged until 2050.
— The modelling period projects until 2100.
— Total capacity of boiler plants was 117 800 GCal/year at the end of 2012.
— The commissioning of new cogeneration plants is not more than 600 MW per year.
— The commissioning of new boiler plants is not more than 200 MW per year.

The modelling of the NES is performed using the following boundary conditions and assumptions:

— Nuclear generation is represented absolutely, as a basic component of the energy system of Ukraine.
— SMRs can be deployed after 2030.
— The Centralized Dry Storage Facility will be commissioned in 2018.
— The nuclear share of the energy mix of Ukraine will be limited to 50%.

[10] See http://mpe.kmu.gov.ua/minugol/control/uk/doccatalog/list?currDir=50358

— One third of heat consumed by the population and communal domestic households may be generated by nuclear power plants.
— The commissioning of new SMRs will not be more than one unit per year (325 MW).

(b) Assumptions for the nuclear fuel cycle analysis

Assumptions for the nuclear fuel cycle analysis included the following:

— Five LWRs (two LWRs installed and three advanced LWRs) with UOX fuel will be commissioned by 2030.[11]
— There is a possibility to commission annually no more than one reactor of any type after 2030.

(c) Code and methods

The modelling of the energy system is performed with the MESSAGE software [3.36]. Input data for both scenarios is presented in Annex XXII.

3.1.9.4. Summary presentation and analysis of the results

The study considers two scenarios: replacement heat generation by small nuclear units; and wide deployment of the SCWRs.

(a) General assumptions of Scenario 1: Replacement heat generation by small nuclear units

According to the 2013 updated energy strategy for Ukraine, total heat consumption is in the range of 216–244 million GCal per year. Domestic household (44%) and industry (35%) were the main consumers. Other sectors of the economy consumed about 21%. The 2013 strategy predicts an increase of heat consumption up to 290 million GCal (at 25%) by 2030.

In the case that fossil fuel generation is replaced by nuclear generation for heat production in domestic households, nuclear reactors would not be located far from large consumers (i.e. in large cities and industrial centres). However, it will not be possible to replace all fossil fuel generation; conservatively, it can be expected that one third of heat consumed by the population and communal domestic households could be generated by nuclear power plants. In the long term, heat consumption in domestic households is proposed to be a constant 100 million GCal per year — constant because energy consumption will decline and energy efficiency will grow. Thus, the substitution level of fossil fuel generation to nuclear generation could be 33 million GCal.

The following constraints are used:

— Nuclear power application for district heating is possible after 2030.
— Commissioning of one reactor per year.

Small sized reactors can be operated in a cogeneration mode. For such a case in Ukraine, the generation structure and share are presented in Figs 3.66 and 3.67. In this, the nuclear power plant share increases, and by 2050 would make up 50% of total generation (cogeneration of heat and electricity). Total installed capacities of large sized reactors are maintained at the level of 15 GW in the long term (see Fig. 3.68). The dynamic of ALWR and SMR commissioning are presented in Fig. 3.69. Spent nuclear fuel accumulation is presented in Fig. 3.70.

Results obtained for the case of SMR exploitation for the electricity and heat cogeneration are presented in Figs 3.71 and 3.72. Results are obtained assuming conditions with no limitation for the heat cogeneration by small sized reactors. The total installed nuclear capacity and schedule of new capacities commissioning are presented in Figs 3.73 and 3.74. Spent nuclear fuel accumulation is presented in Fig. 3.75.

[11] Ibid.

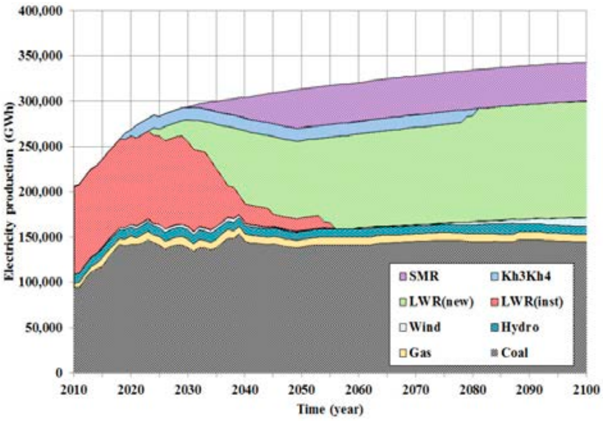


FIG. 3.66. Electricity generation structure.

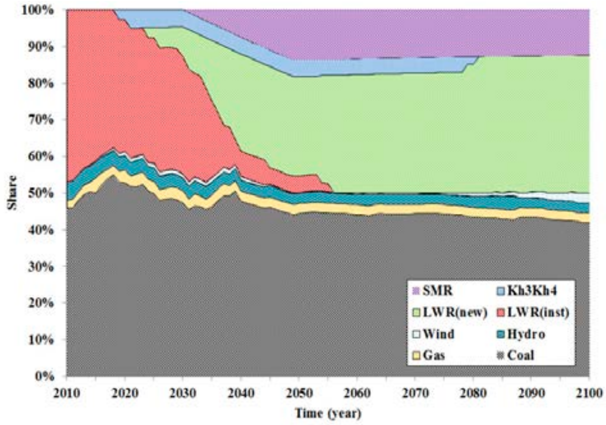


FIG. 3.67. Generation share.

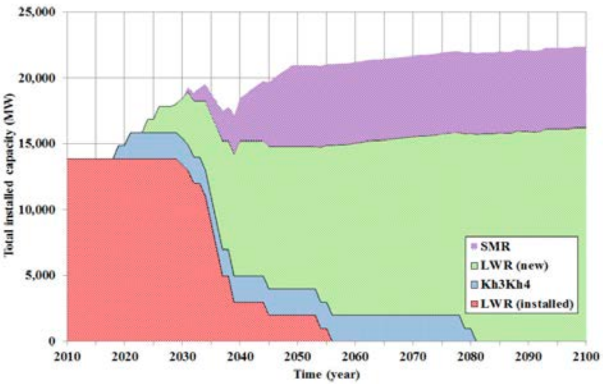


FIG. 3.68. Total installed capacities.

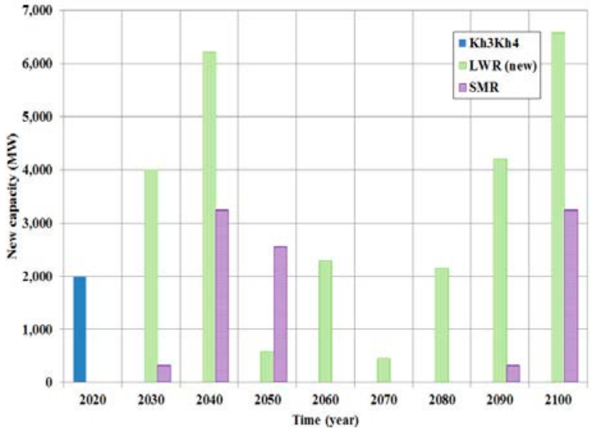


FIG. 3.69. Schedule of new capacities commissioning.

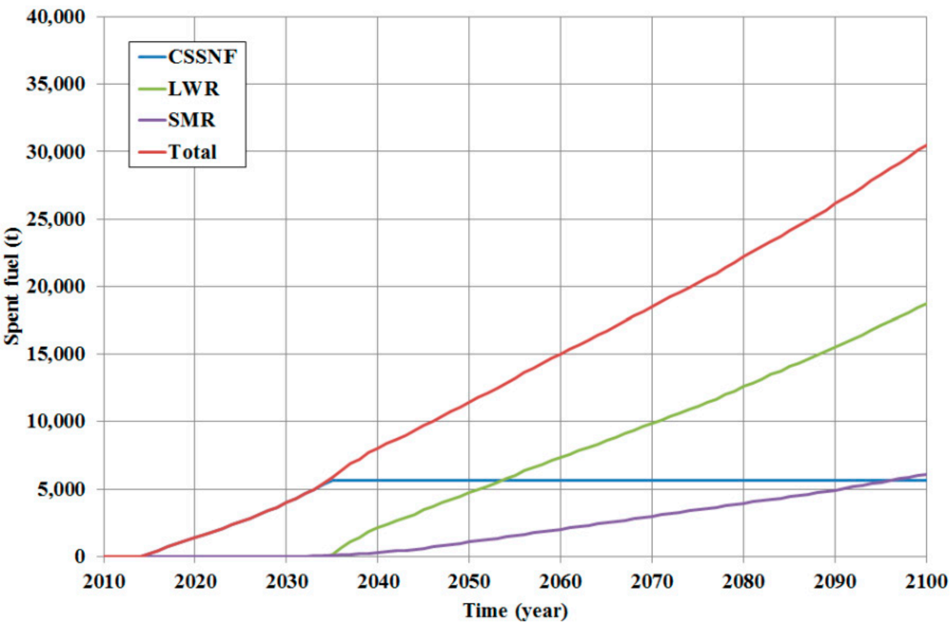


FIG. 3.70. Spent nuclear fuel accumulation.

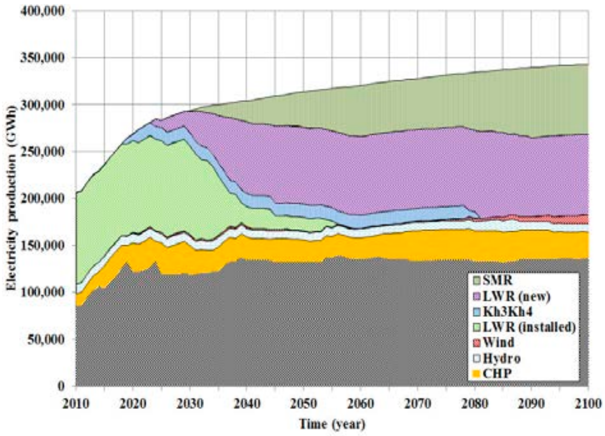


FIG. 3.71. Electricity generation structure.

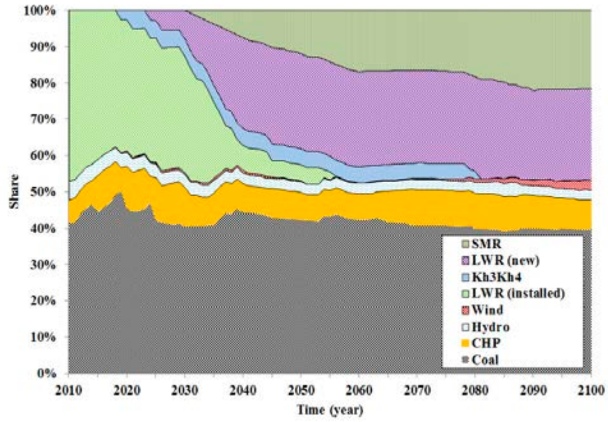


FIG. 3.72. Generation share.

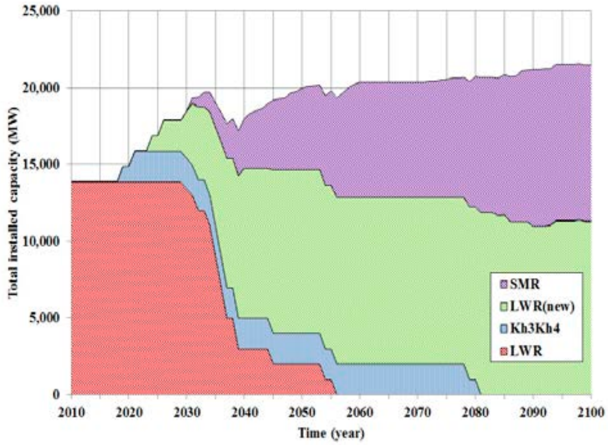


FIG. 3.73. Total installed capacities.

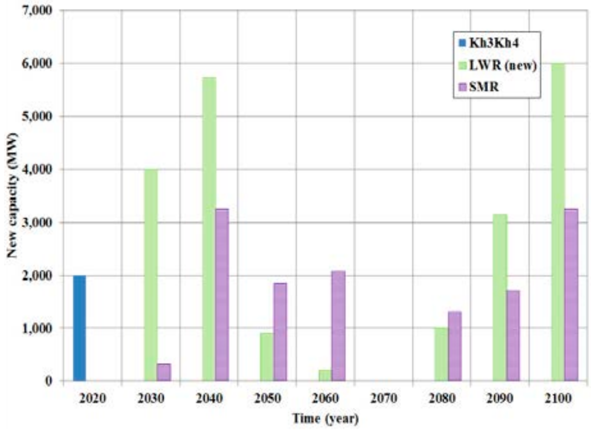


FIG. 3.74. Schedule of new capacities commissioning.

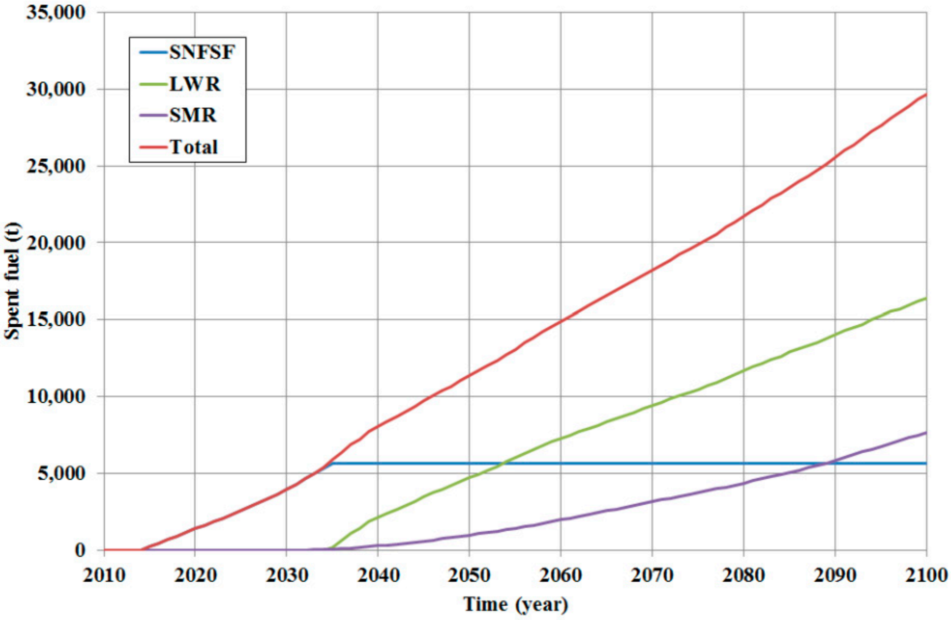


FIG. 3.75. Spent nuclear fuel accumulation.

(b) General assumptions of Scenario 2: Wide deployment of supercritical water cooled reactors

The electricity generation structure and generation share for a scenario in which SCWRs are widely deployed in the energy system of Ukraine are shown in Figs 3.76 and 3.77. The commissioning of SCWRs is not expected before 2030. The total installed capacities and schedule of new commissioning capacities are shown in Figs 3.78 and 3.79. Spent nuclear fuel accumulation is presented in Fig. 3.80.

(c) Analysis of the results under Scenario 1

In the case of SMR implementation in the energy system for heat generation, the generation structure and share of the nuclear power plant increases and by 2050 will have a share of up to 50% from the total generation. Total installed capacities of large sized reactors are maintained at the level of 15 GW in the long term. The rate of construction for new nuclear power units should be high enough to maintain a 50% nuclear share in electricity generation. In 2020–2030, 4 GW of large sized reactors would be commissioned and 6 GW of large sized reactors would be commissioned from 2030 to 2040, plus an additional 3 GW of small sized reactors.

In the case that considers heat generation by boiler plants (i.e. combined heat and power plants and small sized reactors which operate in the mode of electricity and heat cogeneration), the modelling results demonstrate the viability of nuclear power application for electricity and heat cogeneration (district heating) purposes. The scenario considers the replacement of some fossil fuelled power plants by nuclear power plants. Total installed capacity of nuclear power plants would increase up to 20–21 GW. In 2020–2030, 4 GW of large reactors would be commissioned, while 5–6 GW would be commissioned during 2040–2050, 3 GW of 300 MW small sized reactors would be commissioned from 2030 to 2040, and 2 GW of small sized reactors would be commissioned annually from 2050 to 2060. The commissioning of a considerable amount of new nuclear capacities corresponds to the large amount of acting nuclear reactors to be decommissioned in the indicated period. The amount of accumulated spent nuclear fuel will make up about 30 000 t until 2100.

The analysed scenario demonstrates the viability of nuclear power application for district heating. The obtained results should be considered as optimistic because:

- The rate of commissioning nuclear power units is relatively high.
- Although the potential of using nuclear reactors for district heating has been demonstrated, it is not always possible to construct nuclear power plants near large consumers.
- More intensive operation of nuclear reactors means more spent nuclear fuel accumulation. The scenarios assume a once through nuclear fuel cycle with spent nuclear fuel disposal, but the construction of storage facilities is not considered.

(d) Analysis of the results under Scenario 2

Taking into account for increased capital construction costs for Generation III and III+ reactors (over previous generation reactors) as a result of more complicated safety systems, increased time required for commissioning, construction delays and periodical changes in exchange rates, fossil fuelled power plants may be seen as more attractive from an economic perspective. However, increased costs and technical parameters have also increased capital construction costs for fossil fuel generation.

A possible solution is the construction and operation of SCWRs. The first commissioning of SCWRs is not expected before 2030, but as a result of the high technical specifications of SCWRs, the capacity of new SCWRs that could be commissioned in 2030–2040 could generate up to 10 GW. This would allow the share of nuclear power in all electricity generation to remain at 50% — in line with policy requirements for the energy system of Ukraine. This fact is considered as an attractive feature of SCWRs in comparison with approaches involving generation of energy other than electricity. By 2100, the total installed capacity of ALWR and SCWR would be 20 GW.

With utilization of SCWRs, a total of 25 000 t HM of spent nuclear fuel will accumulate by 2100. This amount of spent nuclear fuel is much less in the option based on a once through nuclear fuel cycle (up to 30 000 t HM). This is notable since reprocessing and infrastructure development for minor actinides and plutonium storage would not be required.

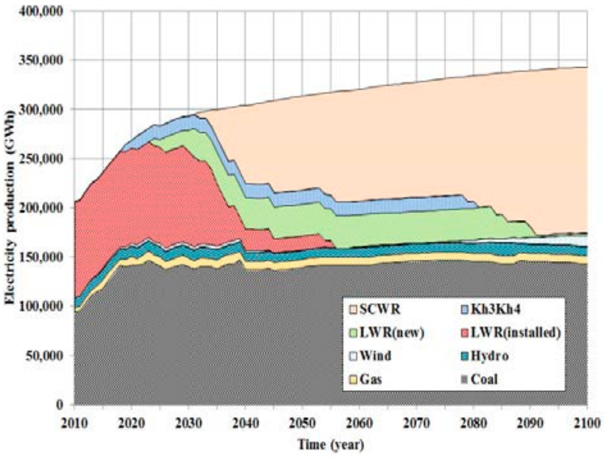


FIG. 3.76. Electricity generation structure.

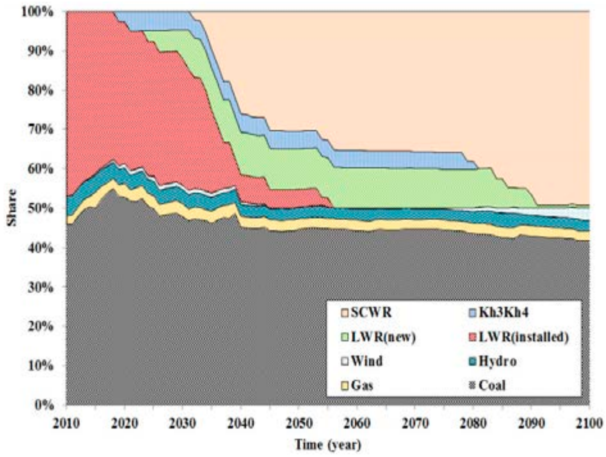


FIG. 3.77. Generation share.

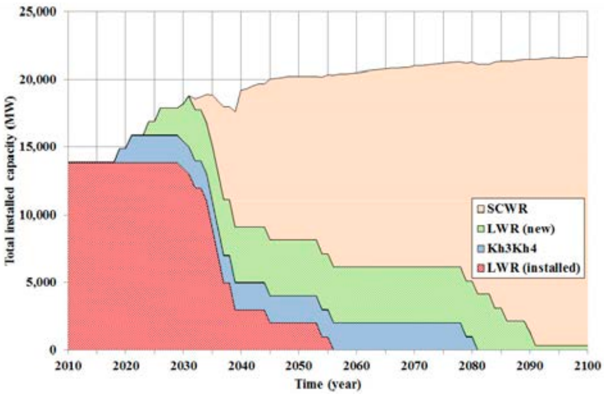


FIG. 3.78. Total installed capacities.

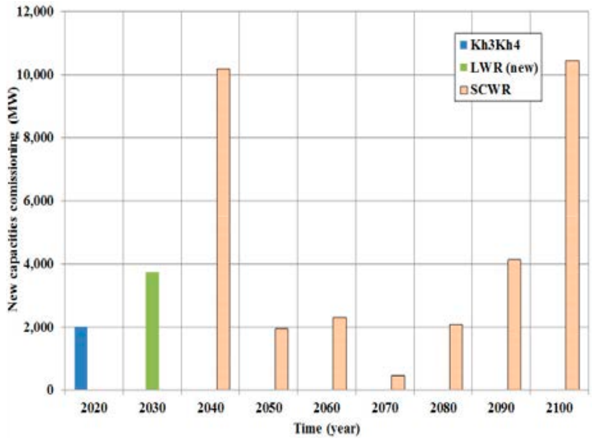


FIG. 3.79. Schedule of new capacities commissioning.

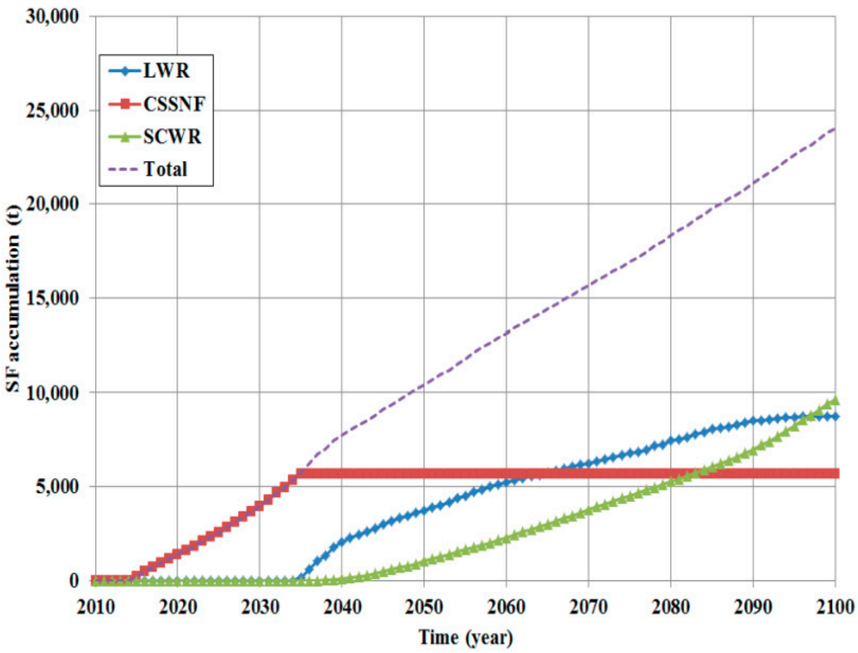


FIG. 3.80. Spent nuclear fuel accumulation.

In consideration of better nuclear fuel utilization in the scenario based on SCWR, natural uranium reserves will be sufficient until 2100, an unfavorable result compared to scenarios based on a closed nuclear fuel cycle with unlimited recource.

3.1.9.5. Conclusions

(a) Scenario 1: Replacement heat generation by small nuclear units

Small reactors have a number of advantages that could be decisive when building an innovative system, including:

- Their small size allows for a significantly shorter construction period and hence reduced investment risks.
- Their capability for different applications in addition to electricity generation: production of industrial heat, sea-water desalination and cleaning, operating in cogeneration mode and central heating.
- Their compactness is advantageous where the construction of large sized units is not feasible (e.g. due to high population density or poor cooling water resources).

Small sized reactors are technically feasible for cogeneration of electricity and heat. If the price for hydrocarbon fuel is high, it could be attractive to use nuclear reactors intensively for heat generation needs (as per input data accepted and model built). However, the use of small sized reactors for base scale electricity generation is a less feasible solution for Ukraine due to high capital costs. Small sized reactors are more attractive if they are deployed for industrial and civil heat generation purposes, as a means to strengthen security of supply in the Ukrainian energy system. However, the system would accumulate a large amount of spent nuclear fuel (30 000 t) as compared to a basic power generation scenario based on the once through fuel cycle.

(b) Scenario 2: Wide deployment of supercritical water cooled reactors

SCWRs are considered to be feasible and attractive, can produce a significant share of electricity in the energy system as a result of their higher technical parameters (increased values of capacity factor, efficiency and fuel burnup rate). Taking into account the technical and economic characteristics applied in this study, the introduction of SCWRs would significantly increase the share of nuclear generation in Ukraine. The results show the economic attractiveness of deploying SCWRs after 2030 in comparison to advanced LWRs. SCWR application would allow for a decrease in spent nuclear fuel accumulation, and is the only feasible approach to maintain a 50% share of nuclear generation in the Ukrainian energy system.

Development of a SCWR fleet is a reasonable approach to consider as a component of a once through nuclear fuel cycle. In this case, international cooperation in the nuclear fuel cycle field will be required only for enrichment of uranium hexafluoride and fuel pellet sintering (until implemented at the domestic nuclear fuel fabrication plant). As for the fuel cycle back end, it may be reasonable to address the capability of establishing a regional complex for long term spent fuel storage, so as to optimize economic expenditures and to minimize deployment of dry spent fuel storage facilities at each nuclear power plant.

3.2. SCENARIOS WITH THE INTRODUCTION OF A NUMBER OF FAST REACTORS TO SUPPORT MULTI-RECYCLING OF Pu IN LWRs AND FAST REACTORS (SCENARIO FAMILY B)

3.2.1. Evaluation of national NESs based on Pu cycle with the introduction of a number of fast reactors

3.2.1.1. Introduction

This section compiles the results of relevant French and Russian scenarios for closing the plutonium cycle with the introduction of a number of fast reactors [3.44–3.47]. The studies presented in this section fall into SYNERGIES Task 1, on the evaluation of synergistic collaborative scenarios of fuel cycle infrastructure development. The complete case study can be found in Annex VII on the CD-ROM accompanying this publication.

3.2.1.2. Objective and problem formulation

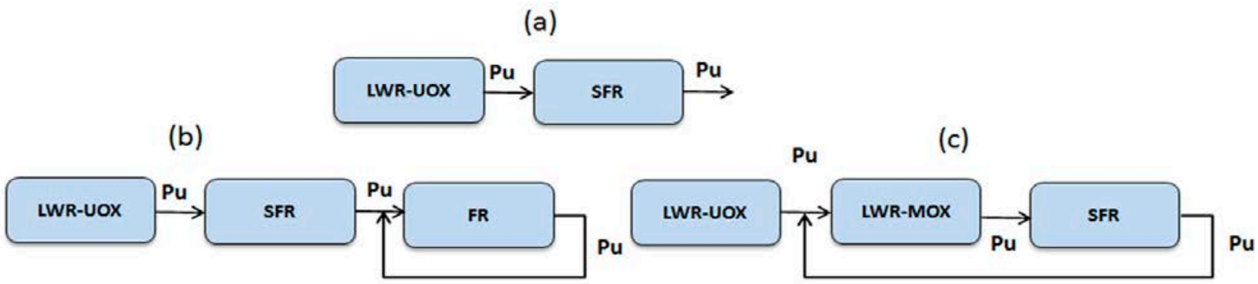
The objectives of the studies compiled in this section are to address the problem of spent nuclear fuel accumulation from LWRs and to decrease natural uranium consumption based on possible closed fuel cycle scenarios involving the introduction of a number of fast reactors under development in France and the Russian Federation [3.44–3.47].

The Électricité de France (EDF) study [3.44] explored different ways of utilizing recovered plutonium in thermal and fast reactors. The current NES in France is based on thermal reactors with uranium fuel and partial loading of MOX fuel with a single recycling of plutonium. In future cycles, plutonium can come from different sources, but the content of plutonium in fresh LWR MOX fuel has to remain under 12% for safety reasons. MOX for SFRs can be produced from plutonium recycling from its own fuel or from LWR spent fuel. The most effective scenarios are based on deployment of large scale fast reactors utilizing their own plutonium with startup on plutonium recovered from thermal reactor spent fuel. However, such a scenario relies on a very large deployment of fast reactors, which may not be possible in the short and medium terms. The EDF study [3.44] showed that plutonium multi-recycling is possible with a symbiotic fleet composed of LWR UOX, LWR MOX and SFRs optimized to reach equilibrium between plutonium consumption and production [3.48]. This scenario minimized the number of SFRs while maximizing the energy produced with LWR MOX using plutonium resources as fuel and are already widely used in the current French fleet. The plutonium produced in UOX LWRs is used to feed LWR MOX as in France, and SFRs are used to recycle plutonium from spent LWR MOX fuel to improve its quality so it can finally be used together with spent UOX fuel to produce fresh LWR MOX fuel (see Fig. 3.81).

In the Russian case studies [3.45–3.47], the authors suggested an option for resolving the problem of spent nuclear fuel based on the use of technologies that rely on the BN type reactors (SFRs) and MOX fuel, as already demonstrated in the Russian Federation. To a certain extent, the variant proposed is similar to that of France. However, unlike the French variant, the Russian one includes the first phase of solving the problem of WWER spent fuel up to 2035 (see Fig. 3.82). The infrastructure for the option proposed includes an industrial plant for the aqueous reprocessing of UOX spent fuel unloaded from the WWER and a facility for fabrication of MOX fuel for BN from plutonium separated from WWER spent fuel. At this phase, it is suggested to fabricate MOX fuel not for recycling in existing WWERs, but for a single run use of plutonium from WWER in a small number of BNs which serve for the utilization of plutonium from WWER spent fuel and could be termed as a ‘BN utilizer’.

Note: (a) First step; (b) Second step.

FIG. 3.81. French scenario: Transition to a sustainable nuclear energy system based on a closed nuclear fuel cycle.



Note: (a) First step; (b) Second step in the case of high nuclear energy demand; (c) Second step in the case of nuclear energy demand stabilization.

FIG. 3.82. Russian scenario: Transition to a sustainable nuclear energy system based on a closed nuclear fuel cycle.

3.2.1.3. Assumptions, methods, codes and input data used

The following scenarios were explored and compared in the EDF study [3.44]:

— Scenario based on SFR for replacing ageing LWRs, so that the French fleet is entirely composed of SFRs at the end of the century (Scenario S_1);
— Partial SFR deployment, the French fleet is thus composed of LWRs, loaded either with UOX or MOX fuels, and SFRs (Scenario S_2);
— SFR deployment being delayed, advanced LWRs with a high conversion ratio (HCLWR) allowing to multi-recycle the plutonium are deployed as from 2050 (Scenario S_3);
— Scenario business as usual (S_BAU) was computed for comparison where the current is replaced by a 60 GW(e) EPR fleet between 2020 and 2050 and remains the same after this year.

The most relevant scenario is the second one, with a limited share of SFR deployment beginning in the medium term with a French fleet composed of LWRs loaded either with UOX or MOX fuels, and SFRs. Scenarios have been computed with the EDF R&D fuel cycle simulation code TIRELIRE–STRATEGIE [3.49] and optimized to meet constraints imposed on the NES, such as a reprocessing facility that temporarily stores masses of separated plutonium and minor actinides under imposed limits and recycles older assemblies first. Details of reactor characteristics are provided in the EDF study [3.44]. For safety reasons, the plutonium content has to be kept under 12% in order to keep negative void coefficient. So the quality of the plutonium in LWR MOX is not enough to be used again in LWR MOX. No limitation has been considered on the fraction of LWRs fed with MOX fuel. The SFR heterogeneous core CFV concept (coeur à faible effet de vide sodium, low sodium void effect core) used for the study was developed by the French Alternative Energies and Atomic Energy Commission (CEA, Commissariat à l'énergie atomique et aux énergies alternatives) [3.50]. It uses internal axial breeder zone, upper sodium plenum, upper absorbing zone, small core height and different heights depending on the radius. This design has been modified to create a 3600 MW(th) core with a breeding gain of nearly 0.18.

The Russian case study [3.45–3.47] assumes possibility to select after 2035 one scenario for implementation from three scenarios which depends on macroeconomic situation in the country.

The optimistic scenario supposes an optimistic market forecast for the construction of new nuclear power plants after 2030. The innovative technologies developed in the framework of the Federal Target Programme Nuclear Power Technologies of the New Generation for the years 2010–2015 and for the perspective till 2020 are assumed to be successfully demonstrated by 2035. The MOX SNF from the BN reactors (in this case they are not utilizers) will be reprocessed using the closed nuclear fuel cycle infrastructure that will be developed for large scale nuclear power development based on advanced technologies. Plutonium separated from the spent fuel of the MOX fuel of the BN reactors will be used for the fabrication of startup loadings of the innovative fast reactors operating within a fully closed nuclear fuel cycle.

The second scenario also assumes a rather optimistic market forecast for nuclear power plant construction after 2035, but takes into consideration that the industrial demonstration of innovative fast reactors and closed nuclear fuel cycle technologies is delayed until the middle of the century. In this case, spent fuel accumulated from the BN reactors could be reprocessed and the plutonium separated can be used for the fabrication of startup loadings of the new BN-1200 operating in a fully closed fuel cycle.

The pessimistic scenario assumes that there will be no increasing demand in nuclear energy after 2035. In this case, solutions to the problems related to the spent fuel will have to be developed in the framework of the system presented in Fig. 3.82, for example via reprocessing of MOX spent fuel generated by BN utilizers and organization of multiple recycling of plutonium in the form of MOX fuel, both in BN reactors and WWERs.

3.2.1.4. Summary presentation and analysis of the results

Partial SFR deployment for the EDF scenario resulted in an equilibrium with 29.5 GW(e) of LWR UOX, 14.5 GW(e) of LWR MOX and 16 GW(e) of SFR. Annual uranium consumption would be 210 t/year/GW(e). This indicator shows that Scenario S_2 could make better use of its advanced reactors.

The plutonium inventory at equilibrium in Scenario S_1 is high — over 1100 t, which is the plutonium inventory for Scenario S_BAU in 2130. Scenarios S_2 and S_3 have also high plutonium inventories of the same magnitude (compared to current inventory) but S_2 has better cycle performance in term of uranium consumption.

Spent fuel reprocessing capacity is driven by the need for plutonium to fuel reactors. At equilibrium, the reprocessing capacity needed by Scenarios S_2 and S_3 is roughly the same and is nearly the capacity in mass of the current plant of AREVA NC La Hague. For Scenario S_1, the reprocessing capacity needed is half in mass, but the plutonium content of spent fuel at equilibrium is 2.5 higher than for other scenarios of plutonium multi-recycling, which will be a challenge for the reprocessing plant.

Current fuel cycles cannot use the plutonium from spent MOX fuel. Therefore, the subassemblies of LWR MOX stay in cooling pools in Scenario S_BAU, which increases the capacity needed. All scenarios used plutonium multi-recycling permits to keep spent fuel storage under 19 000 t, which is consistent with the current French capacity for spent fuel. At equilibrium, the storage needed is low compared to the current state: around 5000 t for Scenarios S_2 and S_3 and 2700 t for Scenario S_1. Nevertheless, Scenarios S_1 and S_2 have to use sodium cooling pools before spent fuel washing, which is technologically more advanced than current water pools.

As all scenarios assume the same production of electricity, the only difference in the mass of fission products melted in glass canisters is the net yield of the reactors. As the net yield is higher in SFRs than in LWRs (40.3% vs ~34%), Scenario S_1 produces less fission products than Scenario S_2, which produces less fission products than Scenario S_3 and Scenario S_BAU. The number of glass canisters is roughly proportional to the fission products sent to waste. In 2150, a total of 8150 t of fission products were sent to waste through the reprocessing unit for Scenario S_1, 8450 t for Scenario S_2 and 8740 for Scenario S_3.

Minor actinides are considered in the scenarios as final waste. At equilibrium, the mass of minor actinides in cycle for Scenarios S_1, S_2 and S_3 are low at 14 t, 22 t and 27 t, respectively. In 2150, Scenario S_3 has a total inventory of minor actinides of 570 t, which is more than a half higher than Scenario S_1 (370 t in 2150). Scenarios S_2 and S_BAU produce the same amount of minor actinides (500 t in 2150). Scenario S_2 produces more minor actinides than the linear combination of reactor production. The reason is that the quality of plutonium in fresh LWR fuel is lower than the one of plutonium from LWR UOX spent fuel and the quality of plutonium in SFR fresh fuel is also decreased by the irradiation in LWR MOX.

The Russian case study emphasizes the need in transition period from NES based on WWER reactors which generates increasing amounts of spent fuel to the plutonium balanced NES based on WWERs/BN reactors. As mentioned above, in the very first phase of the transition, BN reactors works as pure utilizers. The number of BN utilizers is determined from the annual balance of plutonium quantities accumulated in the WWER and the plutonium consumed for the fabrication of MOX fuel for the make-up of the BN utilizer. For example, if the level of plutonium accumulation in the WWER is about 200 kg Pu/GW(e), and annual consumption of plutonium for the manufacturing of MOX fuel for the BN-1200 is about 1200 kg Pu/GW(e), this means that for the utilization of plutonium received from six WWERs, it will be necessary to commission one fast reactor of the same unit power level. Taking into account the additional demand of plutonium for the initial loading of the BN reactor, the resultant relationship in this NES in terms of power between the WWERs and BN utilizers can be defined in the range of 7–9. That is, if we have in the nuclear power system about 10% of power on the BN utilizers, a complete utilization of plutonium from the spent fuel originating from the WWERs will become possible.

For this first phase, commissioning of BN to NES aimed for solving the problem of accumulated spent fuel, and it will be not necessary to construct the elements of infrastructure associated with reprocessing spent fuel from BN reactors. The NES at this phase could include:

— A plant for the aqueous technology of reprocessing the spent fuel from WWERs, with a capacity depending on the total power of the WWER fleet;
— A production line for the fabrication of MOX fuel for BN reactors from plutonium separated from WWERs;
— A total of 4–6 units of BN-1200-utilizers to consume all plutonium from the WWER fleet by 2035.

The share of fast reactors after 2035, when the problem of WWER spent fuel is mainly solved, depends on the specific situation on nuclear energy demand. For the case of nuclear energy demand stabilization, when plutonium production and consumption is balanced, the share of WWER UOX is 37%, the share of WWER MOX with 43% of MOX fuel is 27%, and the share of BN reactors is 36%. It is different, but not drastically, from the French case (49%/24%/27%).

3.2.1.5. Conclusions

The EDF scenarios have considered different ways of plutonium utilization from MOX spent fuel, which is not possible in the current fuel cycle. They help to decrease natural consumption. Scenario S_1 is the most efficient, but relies on a large scale deployment of SFR, which may not be realistic before 2100. Scenario S_2 permits the optimization of the fleet with less advanced reactors and only one fourth comprised of SFRs. This scenario can reduce natural uranium requirements by half. Scenario S_3 demonstrates how advanced LWRs with a high conversion ratio can be considered in a closed nuclear fuel cycle. This solution might be a more economical way to close the fuel cycle, but the performance of the cycle is low compared to Scenarios S_1 and S_2; the reduction of uranium consumption is limited, the plutonium inventory in the cycle is still high, the HLW production is higher, and the capacity of the reprocessing plant would have to be very high.

The Russian study explored the idea of using the demonstrated technologies associated with BN type reactors and MOX fuel to resolve the pressing problems related to the accumulation of SNF from WWER. The authors of the study emphasized the need in transition phase approximately to 2035 to provide construction of a small series of fast reactors and to start radically solving the problem of spent fuel accumulation. It was proposed to build at this phase the facilities for reprocessing of spent fuel from WWER and for fabrication of MOX fuel, as well as several power units of BN-1200 up to 10% of overall nuclear power capacity. This option would allow to create preconditions for further recycling of MOX fuel for complete and efficient solution of the problems of spent fuel from WWERs, with decreasing storage capacity and minimization the accumulation of radiotoxic ^{241}Am during WWER spent fuel storage. Moreover, in contrast with existing options (spent fuel disposal or MOX recycling in LWR), the proposed option would preserve all plutonium accumulated in WWERs in a consolidated form (spent fuel MOX BN) as a startup resource for potential large scale deployment of advanced or innovative fast reactors and closed nuclear fuel cycle technologies currently under development or large scale deployment based on BN technologies in case of high nuclear energy demand. In the case of stabilization of nuclear energy demand, plutonium from spent fuel MOX BN could be recycled as MOX fuel (30–40% of core) in current advanced WWERs followed by multi-recycling in existing BN reactors.

3.2.2. Global scenarios with the introduction of a number of fast reactors under uncertainties in the scale of nuclear energy demand and in the nuclear power structure

3.2.2.1. Introduction

INPRO is striving to promote a global vision of nuclear energy sustainability for the 21st century by conducting NES assessment studies at a global level as well as regional and national levels. The INPRO collaborative project GAINS particularly developed an architecture for global nuclear energy sustainability by addressing related technical, organizational and institutional issues. The GAINS also developed a comprehensive framework that provides a common platform with methodologies for assessment of NESs, keeping in view assumptions and different boundary conditions. This study uses the GAINS framework and provides assessment of global energy scenarios with introducing fast reactors into the energy mix with different uncertainties in demand and structure of nuclear energy. The case study is related to the SYNERGIES Task 1, on evaluation of synergistic collaborative scenarios for fuel cycle infrastructure development. Appendix III provides a brief account of the GAINS approach and a complete description of the case study can be found in Annex VIII on the CD-ROM accompanying this publication. Some intermediate results of the study were presented in Ref. [3.51].

3.2.2.2. Objective and problem formulation

The objective of the study is to explore global scenarios with the introduction of a number of fast reactors under non-synergistic (separate) and synergistic modes of the world NES architecture taking into account uncertainties in the scale of nuclear energy demand and in nuclear power structure. The study in the previous section was focused on synergistic effects arising due to combining of technological systems (reactors and fuel cycles of different types) at the national level of the countries recycling spent nuclear fuel. At the same time, a positive synergistic effect can be also reached at the level of a global NES through cooperation of the countries with different preferences and strategies of nuclear power development.

The case study emphasizes the ‘low’ scenario while considering uncertainties in nuclear energy demand and power structure. Moderate and high growth of global energy demand is considered with possible delays. The possible option to reduce near term spent fuel accumulation is analysed based on existing LWR technologies and future fast reactor introduction with MOX fuel. The potential contribution of a synergistic approach in the form of ‘win-win’ strategies of collaboration among the technology holders and users is quantitatively presented in the case study providing a pathway to nuclear energy sustainability.

3.2.2.3. Assumptions, methods, codes and data used

This study focuses on transition scenarios of NESs for sustainability under uncertainties in nuclear energy demand and power structure. The study is based on the framework of the GAINS collaborative project [3.52] and analysis provided in Ref. [3.53]. The study considers nuclear energy demand assumptions of the GAINS framework along with a low demand scenario L with possible delays in moderate demand scenario M and high demand scenario H (see Fig. 3.83).

The L scenario is assumed to be near term and up to 2030 for all scenarios under consideration. The M scenario starts in 2030 with a delay of 15 years whereas the H scenario starts in 2050 with delay of about 20 years against medium and high growth scenarios of the GAINS project (see Fig. 3.83). The current study uses nominal grouping of global nuclear power structure based on nuclear fuel cycle strategies adopted by the countries as developed in the GAINS framework and called NG groups. According to this division, the synergistic collaboration takes place between counties such that NG1 countries pursue a fast reactor programme and recycle spent fuel, NG2 countries either directly dispose spent fuel or send it to the NG1 for reprocessing and NG3 countries send their spent fuel to NG1 or NG2 countries for recycling or disposal. The nominal GAINS scenario considers a fixed share of nuclear energy generation by the groups with a ratio of NG1:NG2:NG3 at 40:40:20 by the end of the century.

In the GAINS framework, it was considered that fast reactors were introduced after 2030 in order to optimize the uranium fuel utilization and reduce spent nuclear fuel. The large scale fast reactors utilized plutonium from reprocessed LWR spent fuel as their first loading. The present study uses reactor data from the GAINS database as shown in Table 3.21. The reactor data includes:

- LWR: low burnup LWR.
- FR: break-even fast reactor with breading ratio approximately 1.0, generalized from the BN-800 fast reactor design technology of the Russian Federation.
- FR1: medium breeding ratio (~1.2) fast reactor, exemplified by the Indian prototype fast breeder reactor.

The uncertainty in nuclear energy demand and delays in introduction of fast reactors on a large scale into the energy mix in future may lead to drastic spent fuel accumulation from LWRs after the middle of this century. Reprocessing of spent fuel may be considered as one option to cope with such a situation. This option would consider separating uranium and plutonium to manufacture MOX fuel for single time recycle in presently operating thermal reactors and ultimate geological disposal of HLW. Such an option may help in partially resolving the problem of spent fuel accumulation by decreasing the current annual volumes of spent fuel by a factor of 7, but it will create another problem of accumulation of MOX spent fuel.

A more viable option to reduce spent fuel accumulation in the near future is shown in Fig. 3.84 and involves use of existing LWRs and fast reactors with MOX fuel. According to this option, all spent fuel discharged from UOX fuel loaded in LWRs is reprocessed and MOX fuel will be fabricated from the separated plutonium. This MOX fuel would not be directly used in existing LWRs; instead, it would be used in existing fast reactors for utilizing the plutonium from the spent fuel of LWRs for the L scenario implementation. In this way, all LWR spent fuel would be utilized effectively during the first phase of the L scenario. The reprocessed uranium would be accumulated during such a scenario. However, it is feasible since the reprocessed uranium can be recycled effectively in LWRs and PHWRs, and may also be used in fast reactors and some other reactor types. The present study assumes that the reprocessed uranium from LWRs is converted, re-enriched individually or blended with enriched uranium and finally fabricated into UOX fuel. Such use of reprocessed uranium helps in removing reprocessed uranium from the stock and reducing natural uranium utilization, leading towards nuclear energy sustainability. The depleted uranium occurring in tails of enrichment process of reprocessed uranium can be consumed up in fast reactors in addition

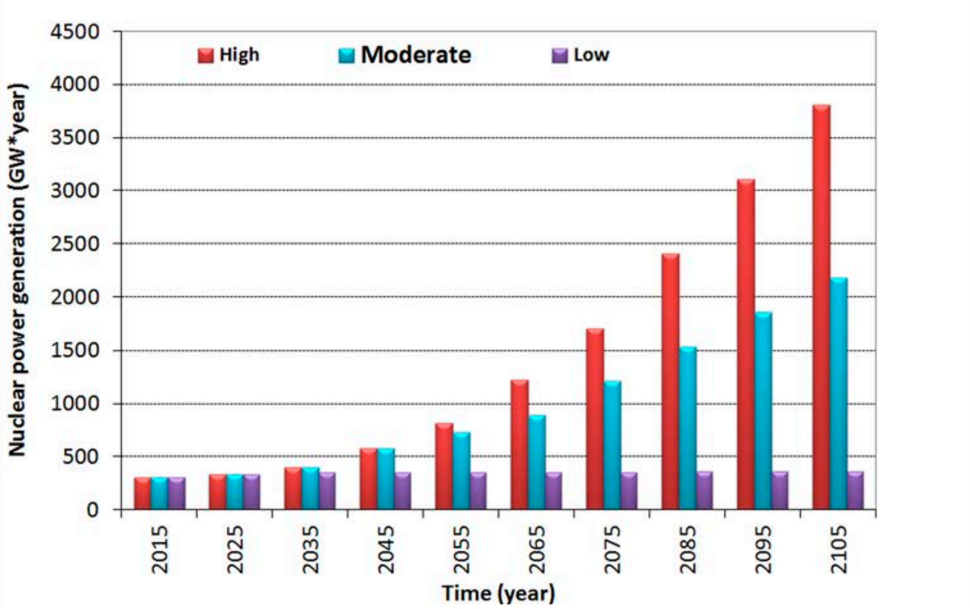


FIG. 3.83. Low scenario and moderate and high scenarios with delay in demand growth.

TABLE 3.21. REACTOR CHARACTERISTICS

Parameter	LWR	FR	FR1
Fuel type	UOX	Pu_depleted U	Pu_depleted U
Electric capacity (MW)	1000	870	500
Thermal efficiency	0.33	0.42	0.40
Load factor	0.85	0.85	0.85
Avg. burnup (MW·d/kg HM)	45	65.9	76.5
Lifetime (years)	60	60	60
U enrichment (%)	4	—	—

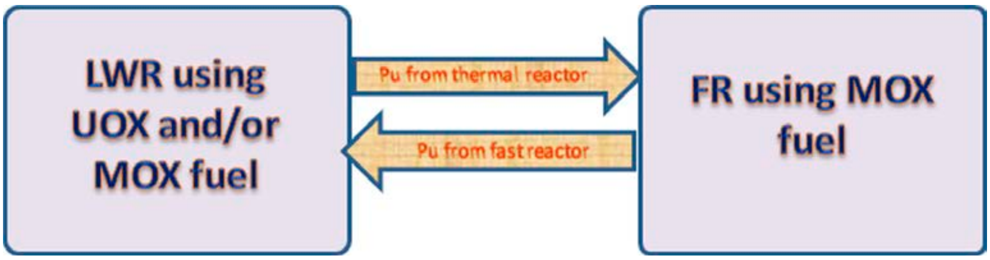


FIG. 3.84. Multiple recycling of plutonium in the form of MOX fuel in fast reactors and light water reactors.

to reprocessed uranium from fast reactors. The reprocessed waste stock will only accumulate minor actinides and fission products in this way.

The prospects of future spent fuel utilization from fast reactors using MOX fuel during implementation of the second phase of the L scenario depend upon demand for nuclear energy, market feasibility for construction of nuclear power plants after 2030 and the readiness of closed fuel cycle technologies and fast reactors. These uncertainties in nuclear energy demand and timeline for innovative fast reactor introduction lead towards considering delays in medium and high scenarios of nuclear power in the present study. Such scenarios were modelled using the MESSAGE tool.

The GAINS framework proposed LUEC as one of the key indicators for assessment of transition scenarios of sustainable NESs. The LUEC calculations are performed using the NEST tool developed by INPRO. Although overnight capital cost and operation and maintenance costs are major constituents of the LUEC, the present study focuses on fuel cycle cost component of the LUEC. The fuel cycle cost component includes costs of all fuel cycle steps from mining to ultimate waste disposal in a nuclear fuel cycle scheme. The reference data used in the study for calculating the fuel cycle cost component of LUEC is presented in Table 3.22.

The economy of scale plays a significant role in per kg cost depending on the size of new facilities [3.8, 3.11]. Therefore, large commercial facilities can be considered for deployment. As shown in Table 3.23, the fuel cycle facilities with high costs are scaled to a national facility N for a smaller power programme (4–6 GW(e)) and to an international facility I for a synergistic large scale nuclear power programme (140–170 GW(e)). The reference facility R represents a reference size fuel cycle facility for a large national nuclear power programme (20–30 GW(e)). The correlated cost changes due to facility size variation (see Table 3.23).

TABLE 3.22. FUEL CYCLE REFERENCE SERVICE COST (APPENDIX II)

Fuel cycle step	Range of service cost	Reference service cost
Uranium (US \$/kg HM)	80–450	80–450
Conversion (US \$/kg HM)	5–10–15	10
Enrichment (US \$/SWU)	8–110–120	110
Fuel UOX (US \$/kg HM)	200–275–300	275
FR1 spent fuel storage (US \$/kg HM)	200	200
LWR spent fuel direct disposal (US \$/kg HM)	400–800–1600	800
HLW direct disposal (US \$/kg HM)	400	400

TABLE 3.23. FUEL CYCLE NATIONAL FACILITY–REFERENCE FACILITY–INTERNATIONAL FACILITY (N–R–I) COST

Fuel cycle step	National/reference/ international facility	Nuclear power, GW(e)	Facility capacity (million SWU/year and t HM/year)	Service cost (US \$/kg SWU and US \$/kg HM)
Enrichment	N	4	0.5	110
	R	22	3	110
	I	145	20	110
Fuel fabrication, MOX	N	4.5	50	3000
	R	23	250	1500
	I	140	1500	750
Reprocessing, UOX	N	5	100	2700
	R	25	500	1300
	I	145	3000	580
Reprocessing MOX and FR1 blankets	N	5.7	100	3000
	R	29	500	1500
	I	170	3000	750

Note: FR — fast reactor; HM — heavy metal; MOX — mixed oxide; SWU — separative work unit; UOX — uranium oxide.

3.2.2.4. *Summary presentation and analysis of the results*

Slow growth of nuclear energy demand is represented by the L scenario in Fig. 3.83. The problem of utilization of spent fuel from fast reactors using MOX fuel is considered using existing structure of NES for this scenario. A suitable solution is introduced in Fig. 3.84, which involves reprocessing of spent fuel of MOX fuel based fast reactors and multiple recycling of plutonium in the existing fast reactors and LWRs in the form of MOX fuel.

Two cases of collaboration are analysed and compared for consumption of natural uranium, spent fuel accumulation and nuclear fuel cycle infrastructure requirements. The first is the back end non-synergistic case (see Fig. 3.85) and involves cooperation between NG1 and NG3 such that NG1 supplies UOX fuel to NG3 without the return of spent fuel. The second is the back end synergistic case (see Fig. 3.86) and involves synergistic collaboration such that NG1 supplies fresh fuel to NG3 including its MOX fuel with return of spent fuel.

(a) Back end non-synergistic case

The nuclear power production growth structure in NG1 is shown in Fig. 3.87 for the back end non-synergistic case. The share of fast reactors increases steadily to 18% and is maintained after 2070. Figure 3.88 shows corresponding spent fuel storage requirements. The spent fuel accumulation from LWRs stabilizes by the end of the century at the same level as the beginning of the century, with 18% share of the fast reactors in NES. The cooling time of LWR spent fuel is assumed to be six years in accordance with the GAINS framework. Although longer LWR spent fuel storage time makes its reprocessing more economical and simpler due to mature reprocessing technology, however longer storage time of spent fuel causes accumulation of large quantity of radiotoxic minor actinide ^{241}Am from the decay of ^{241}Pu. In France, the optimal time of storage before reprocessing spent fuel from

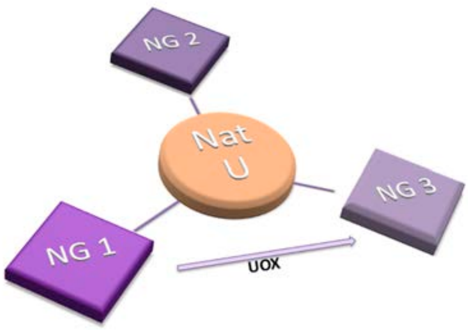


FIG. 3.85. Back end non-synergistic case.

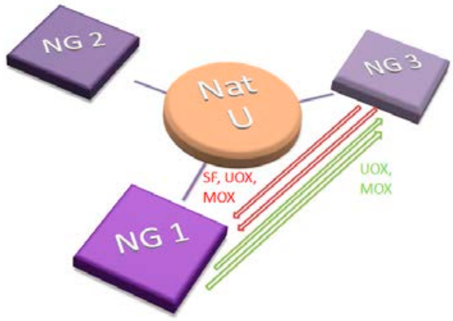


FIG. 3.86. Back end synergistic case.

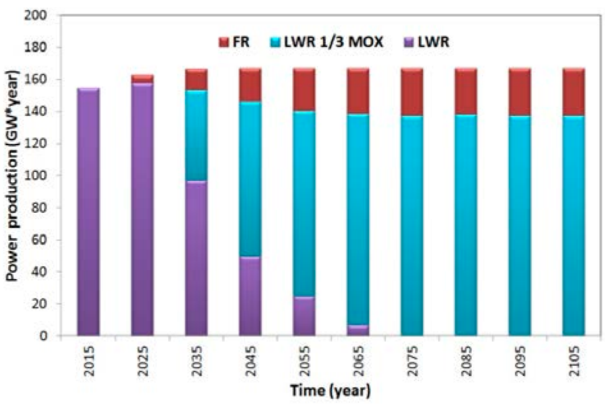


FIG. 3.87. Structure of power production growth in NG1 (back end non-synergistic case).

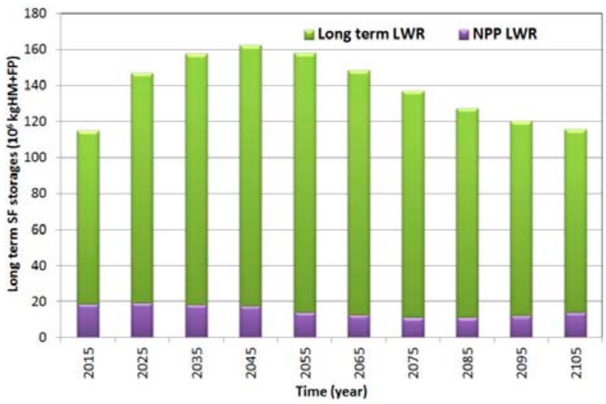


FIG. 3.88. Storages of light water reactor spent fuel in NG1 (back end non-synergistic case).

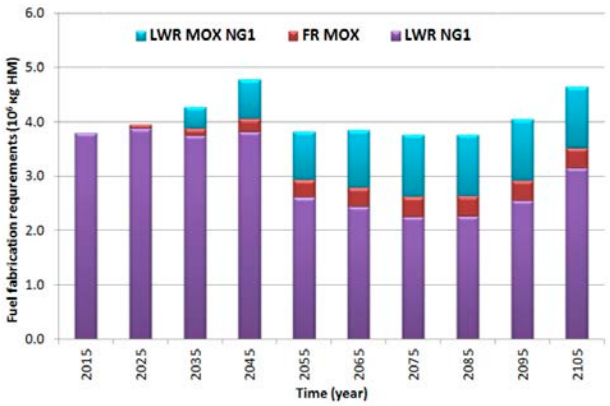


FIG. 3.89. Fuel fabrication (back end non-synergistic case).

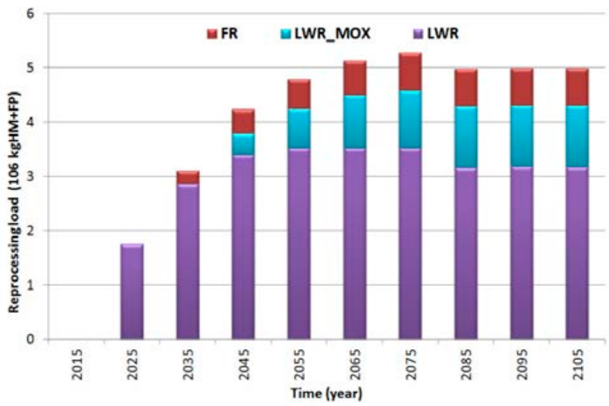


FIG. 3.90. Reprocessing load (back end non-synergistic case).

PWRs is 4–5 years. The ^{241}Am can be separated from spent fuel during reprocessing and discarded in vitrified HLW along with other minor actinides and fission products. Thus, plutonium can be extracted in relatively pure form during reprocessing of UOX spent fuel and MOX fuel for use in fast reactors and can be fabricated avoiding radiotoxic environment.

The upgradation of fuel cycle infrastructure for utilizing spent fuel from LWRs would be required in back end non-synergistic case in the form of additional stages for reprocessing of spent MOX fuel and refabrication of MOX fuel for use in both fast reactors and LWRs (see Figs 3.89 and 3.90). The multiple recycling of plutonium is possible due to the presence of a limited number of fast reactors in the NES. It is achieved by separating low grade plutonium from spent fuel of MOX fuelled LWRs and fabricating MOX fuel for fast reactors which can utilize this reduced quality plutonium effectively. NG1 and NG3 can also opt for cooperation in this scenario for utilization of NG3 spent fuel. NG1 can take back spent fuel from NG3 for reprocessing and fabrication of MOX fuel for use in fast reactors. NG1 can consider adding few additional fast reactors for utilizing the plutonium from NG3 and can also supply MOX fuel to NG3 for loading in LWRs (back end synergistic case, see Fig. 3.86).

(b) Back end synergistic case

The back end synergistic case involves NG1 providing fresh fuel including MOX fuel to NG3 for LWRs, and taking back UOX and MOX spent fuel from NG3 (see Fig. 3.86). The electrical energy generation from fast reactors for both cases is shown in Fig. 3.91. The fast reactor share in the NES increases to 21% for the back end synergistic case from previously described 18% share for back end separate case. The slight increase in fast reactors is observed which utilize plutonium from spent fuel of LWRs of NG3.

Long term storage requirements for spent fuel for the back end synergistic case are shown in Fig. 3.92. The on-site cooling time for LWR spent fuel is considered as six years. The long term storage facilities of NG1 also receive UOX and MOX spent fuel from NG3 for reprocessing. There is a negligible increase in long term spent fuel storage requirements in the back end synergistic case when compared to the back end separate case.

The fuel fabrication and reprocessing load at NG1 is considerably increased in the back end synergistic case for providing fabrication and reprocessing services to the NG3, as shown in Figs 3.93 and 3.94. The transport of UOX and MOX fresh and spent fuel between NG1 and NG3 pose an additional issue which is not considered in this analysis.

(c) Transition to moderate and high scenarios

Nuclear energy demand can rise in medium or long term depending upon favorable market conditions making NES transition towards medium or high demand scenarios. The M scenario is represented by low growth of nuclear energy demand until 2030 and medium energy demand growth continued after 2050. The H scenario suggests low demand growth until 2030, medium demand growth until 2050 and high demand growth afterwards (see Figs 3.95 and 3.96). The increased energy demand growth can be met by MOX fuelled FR1 type fast reactors (breeding ratio = 1.16) in these scenarios. FR1 reactors can utilize spent fuel produced by MOX fuelled fast reactors during

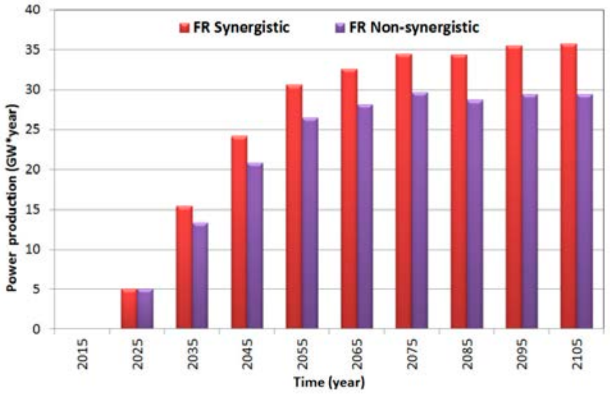


FIG. 3.91. Electric energy production from fast reactors (back end non-synergistic and synergistic cases).

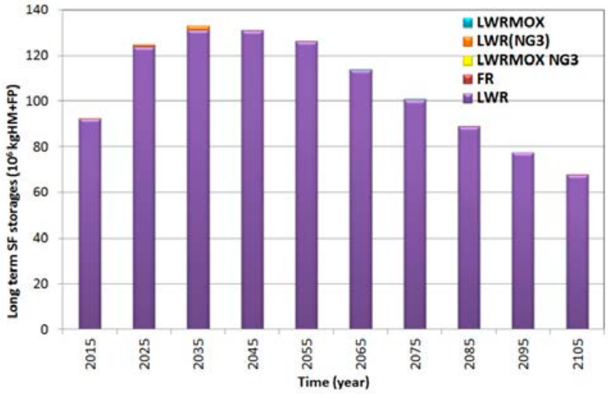


FIG. 3.92. Long term storages of light water reactor spent fuel in NG1 (back end synergistic case).

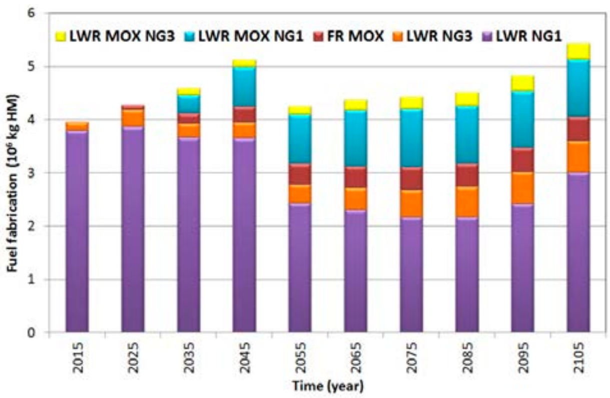


FIG. 3.93. Fuel fabrication (back end synergistic case).

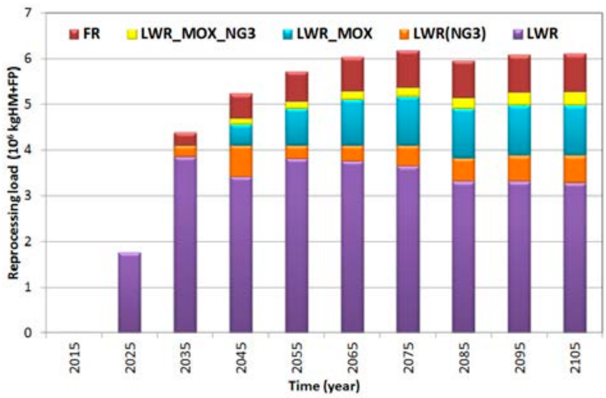


FIG. 3.94. Reprocessing load (back end synergistic case).

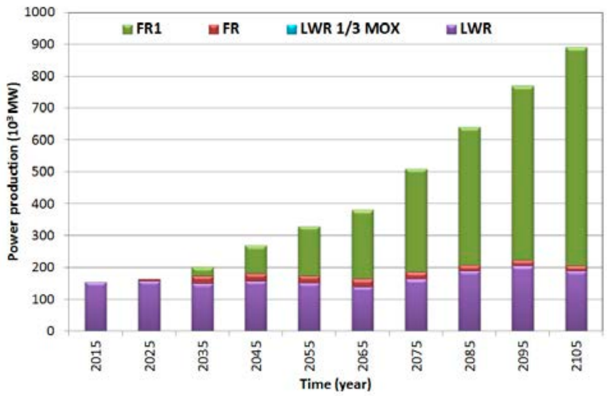


FIG. 3.95. Structure of power production growth (M scenario).

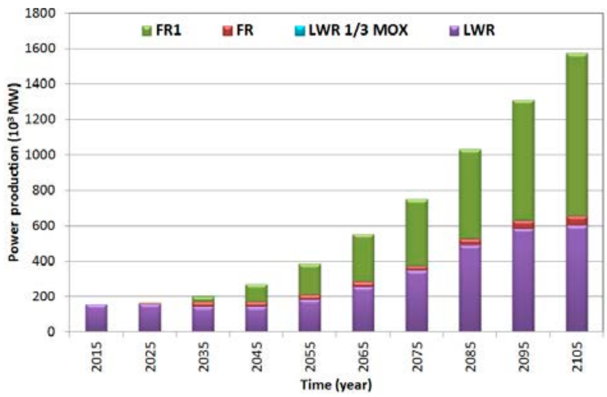


FIG. 3.96. Structure of power production growth (H scenario).

implementation of the first phase of the L scenario. The spent fuel of MOX fuelled fast reactors can be reprocessed and extracted plutonium can be used in fabrication of MOX fuel for utilization in FR1 operating in a closed fuel cycle. However, further upgradation of nuclear fuel cycle facilities would be required for reprocessing of spent fuel from MOX fuelled FR1 reactors and refabrication of MOX fuel from the extracted plutonium for FR1 reactors.

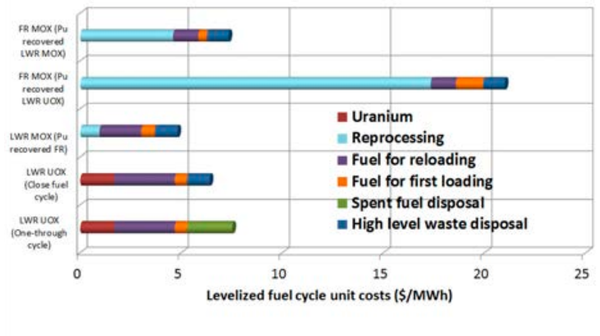


FIG. 3.97. *Levelized fuel cycle unit costs for the reference approach.*

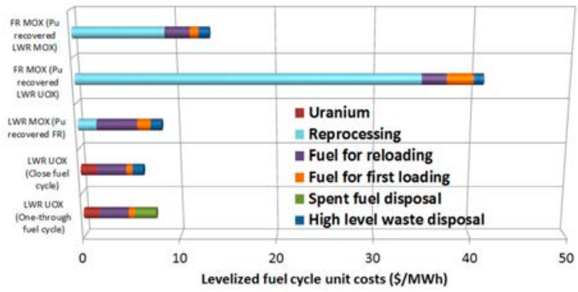


FIG. 3.98. *Levelized fuel cycle unit costs for the international approach.*

(d) Economic considerations for plutonium recycling in thermal and fast reactors

The fuel cycle component of LUEC for all fuel cycle steps of uranium mining, reprocessing, fuel first load and reload fabrication, spent fuel disposal and HLW disposal are calculated using reference cost units and international cost units as shown in Figs 3.97 and 3.98. The calculations are done for both options of a once through open fuel cycle based on LWRs and a closed fuel cycle utilizing multiple recycling of plutonium with LWRs and fast reactors. The spent nuclear fuel reprocessing at an international centre would reduce the reprocessing costs and increase economic competitiveness of the closed fuel cycle option.

Back end synergistic cooperation can be formed in which the NG1 country group can take back spent fuel from NG3 countries for reprocessing and fabrication of MOX fuel for its fast reactors. An addition of few fast reactors would be required at NG1 for utilizing plutonium coming in spent fuel of NG3. Additional facilities for the supply of MOX fuel for LWRs of NG3 would also be needed. Any further increase in nuclear energy demand in medium and long term could be met by adding MOX fuel based FR1 type fast reactors (breeding ratio of ~1.2). The startup fuel for FR1 type fast reactors can utilize plutonium extracted from spent fuel of MOX fuelled fast reactor types along with recycling of their own fuel in a subsequent closed fuel cycle.

3.2.2.5. Conclusions

The present study focused on the impact of uncertainties in nuclear energy demand growth and the scale of nuclear power structure on transition scenarios to globally sustainable NESs. The analysis was performed using the GAINS framework for low energy growth scenario and for delayed moderate and high energy demand growth. The low demand scenario analysis shows that the spent fuel accumulation problem can be resolved by using existing LWRs and fast reactors with MOX fuel in the near term. The plutonium extracted from spent fuel of MOX fuel based fast reactors can be recycled as MOX fuel for 1/3 core loading in existing advanced LWRs and then multi-recycled in existing fast reactors. It is pertinent to mention that all fast reactors with a breeding ratio of 1.0 and 1.2 considered in transition scenario analyses in the current study are based on nearer term fast reactor technologies such as SFRs. Such reactors are either in the construction phase or at advanced stages of project development in several technology holder countries.

3.3. FAST REACTOR CENTRED SCENARIOS ENVELOPING SCENARIOS WITH REPROCESSING OF THERMAL REACTOR FUEL TO ENABLE NOTICEABLE GROWTH RATE OF FAST REACTOR CAPACITY (SCENARIO FAMILY C)

3.3.1. Summary of EU scenarios with transmutation option for nuclear phase out and continued nuclear scenarios

3.3.1.1. Introduction

The study analyses EU scenarios with transmutation options for nuclear phase out and continued nuclear scenarios based on the EC Framework Programme projects Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Nuclear Waste Disposal (RED-IMPACT), Partitioning and Transmutation European Roadmap for Sustainable Nuclear Energy (PATEROS) and ADS and Fast Reactor Comparison Study (ARCAS).

The RED-IMPACT project [3.54] studied the impact of partitioning and transmutation, conditioning and waste reduction technologies on reducing the burden associated with radioactive waste management and disposal. The project focused on realistic evaluation of partitioning and transmutation technologies which can be deployed on an industrial level or based on future developments that take into account inventory of existing and foreseen nuclear fuel facilities in Europe.

The PATEROS project established a global partitioning and transmutation roadmap leading up to the industrial scale deployment of necessary facilities at the European level.[12] A common objective of all strategies using partitioning and transmutation is to reduce the burden on a long term waste management, in terms of radiotoxicity, volume and heat load of HLW, which has to be disposed of in final repositories. Possible strategies can range from using dedicated transmuters in a separate fuel cycle stratum in a stable or expanding nuclear energy scenario in order to reduce drastically the amount of nuclear waste sent to the repository, down to the scenario of a nuclear phase out.

The ARCAS project supports the Sustainable Nuclear Energy Technology Platform (SNETP) Strategic Research Agenda [3.55]. It compared, on a technological and economic basis, accelerator driven systems (ADSs) and fast reactors as minor actinide burners. The economic impact of both options was evaluated for investment cost and operational cost, but not for R&D cost requirements. The project considered technological maturity and how this can be incorporated in the economic analysis.

This study falls within the framework of SYNERGIES Task 3, evaluation of options for minor actinide management, providing technical and economical assessment and comparison of fast reactors and ADSs for transmutation of minor actinides at a European level. Examination of collaborations among European countries also contributed to Task 1, on evaluation of synergistic collaborative scenarios of fuel cycle infrastructure development, for example considering scenarios for sharing of facilities and services and identifying timeframes for required infrastructure introduction and expansion in different stages of the nuclear fuel cycle. The complete case study can be found in Annex XXIV on the CD-ROM accompanying this publication.

3.3.1.2. Objective and problem formulation

One of the main tasks of the RED-IMPACT project was to select representative fuel cycle scenarios to explore the impact of partitioning and transmutation technologies on the overall waste management, and specifically on a final HLW repository [3.54]. The PATEROS project had the objective of establishing a European vision for deployment of partitioning and transmutation of nuclear waste which can contribute to the deployment of sustainable nuclear energy. A regional approach was adopted to implement the innovative fuel cycles associated with partitioning and transmutation in Europe addressing the impact of different strategies in various countries. The ARCAS study aimed to compare, on a technological and economical basis, ADSs and fast reactors as minor actinide burners [3.55]. It is split into five work packages: the reference scenario definition, the fast reactor system definition, the ADS definition, the fuel reprocessing and fabrication facilities definition, and the economical comparison.

[12] For further information on the PATEROS project and the deliverables of the Sixth Framework Programme, see http://pateros.sckcen.be

3.3.1.3. Assumptions, methods, codes and input data used

Reference [3.54] reports that the scenarios that were addressed in the RED-IMPACT project ranged from direct disposal of the spent fuel to fully closed cycles with fast neutron reactors or ADSs. Both equilibrium and transition analyses have been applied to those scenarios. The choice of scenarios was based on a comprehensive representation of waste streams appearing in scenarios discussed in different EU Member States. The indicators assessed included "total radioactive and radiotoxic inventory, discharges during reprocessing, thermal power and radiation emission of the waste packages, corrosion of matrices, transport of radioisotopes through the engineered and geological barriers or the resulting doses from the repository" [3.54]. The selected scenarios included several industrial scenarios in which both equilibrium and transition options were investigated:

— Scenario A1 using LWR reactors, UO_2 and once through cycle;
— Scenario A2 with LWR reactors and UO_2 + MOX (once plutonium recycling);
— Scenario A3 with introduction of fast spectrum only for plutonium reuse and innovative scenarios;
— Scenario B1 representing a Generation IV solution based on an integral fast reactor;
— Scenario B2, similar to A2 but with the introduction of ADSs in a second stratum for transmutation of remaining plutonium and minor actinides;
— Scenario B3, a double state scenario with LWR (UO_2 + MOX) and fast reactor in first stratum and ADSs with minor actinide burning in second stratum.

The PATEROS project considered implementation of partitioning and transmutation and advanced fuel cycles on a regional European level. It studied the possibilities to share fuel cycle facilities and to envisage the optimized use of resources and investments for developing sustainable nuclear energy at a regional level. To provide a regional perspective consideration, countries have been grouped as follows:

— Group A: Stagnant or phase out; focus on spent fuel management.
— Group B: Continuation scenario with focus on optimization of plutonium for future deployment of fast reactors or ADSs.
— Group C: Subset of Group A, after stagnation, envisages a nuclear 'renaissance'.
— Group D: Initially no nuclear power, decides to go for nuclear energy in the future.

Four different scenarios based on the use of fast spectrum reactors and ADSs are studied. Scenarios 1 and 2 considered deployment of ADSs shared by country Groups A and B. ADSs will use the plutonium of Group A and transmute minor actinides of both groups. Plutonium of Group B is either mono-recycled in PWRs and then stored for future deployment of fast reactors (Scenario 1) or continuously recycled in PWRs (Scenario 2). Scenario 3 considered deployment of a group of fast reactors in Group B using plutonium from Groups A and B with the objective of decreasing stock of spent fuel of Group A. Scenario 4 assumed some selected countries decided to relaunch nuclear energy with fast reactors, while other countries continue with their objective of waste minimization. The PATEROS simplified flow scheme is given in Fig. 3.99. The transmuter uses plutonium of Group A and transmutes the minor actinides of the two groups.

The reference scenario considered in the framework of the ARCAS project [3.55] refers to the PATEROS project where a regional scenario, at a European level, was analysed in detail.[13]

In the Collaborative Project for a European Sodium Fast Reactor (CP–ESFR), a 'working horse' SFR design was elected (actually a basic SFR concept), and its parameters were then optimized to improve reactivity coefficients [3.56]. A short description of the optimized reactor concept is provided in Annex XXIV on the CD-ROM accompanying this publication.

3.3.1.4. Summary presentation and analysis of the results

The material balances for plutonium and minor actinides have been calculated for all RED-IMPACT scenarios. It has been shown that the production of plutonium and minor actinides could be reduced by using an

[13] Further information is available from https://cordis.europa.eu/result/rcn/57137_en.html

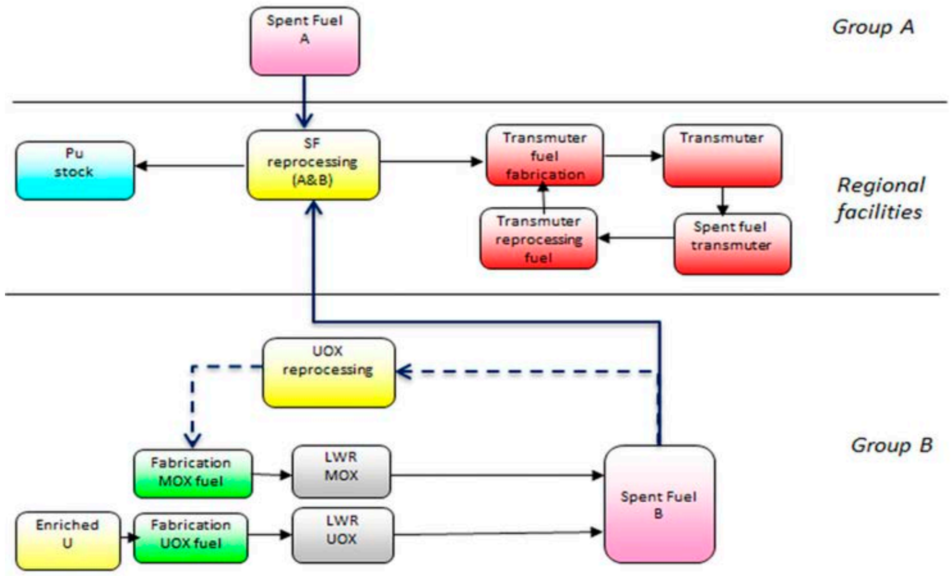


FIG. 3.99. Simplified flow chart used in the PATEROS project.

inert matrix or thorium matrix fuel in LWR type reactors. When plutonium is multi-recycled in LWRs, the amount of generated plutonium waste would be 5–10 times less compared to the case of plutonium mono-recycling, while an increase by a factor of 3–7 would be observed in the amounts of americium and curium. Modelling of the transition scenarios from the current reactor fleet to a final equilibrium state has shown that it is not possible to ignore the radiotoxic inventory of the HLW produced before the deployment of partitioning and transmutation. Fastest possible deployment of partitioning and transmutation could secure a true reduction of the total radiotoxic inventory of HLW in geological disposal. When caesium and strontium are also separated in the partitioning and transmutation cycle, this helps to achieve minimum thermal output of HLW allowing a substantial reduction in the repository size.

The main results of the PATEROS regional partitioning and transmutation Scenarios 1 and 2 can be summarized as follows. The stock of spent nuclear fuel in Group A can reach 0 by 2100, as all the fuel will be reprocessed by then. The plutonium inventory available by the end of the century for future fast reactors in Scenario 1 will be 840 t. The Scenario 2 simulation indicates the main stock of plutonium inventory for Group B to be stabilized at 100 t by 2100. In this, the total inventory would increase slightly over time owing to the accumulation of ‘bad quality’ plutonium produced during MOX multi-recycling, which also has less minor actinide production by radioactive decay with respect to plutonium mono-recycling.

For the proposed transmutation strategy, a total reprocessing capacity of 3700 t per year in Scenario 1 and 3300 t per year in Scenario 2 are needed. The reprocessing capacity for PWR fuel as needed in Scenario 1 is around 18% higher than that available in France currently. When it comes to the ADS reprocessing facilities, they would need to be developed and deployed in the future. The requirements for fuel fabrication capacity are as follows:

(i) Scenario 1:
 — 1000 t/year for UOX;
 — 100 t/year for MOX;
 — 30 t/year for ADSs.
(ii) Scenario 2:
 — 690 t/year for UOX;
 — 390 t/year for MOX;
 — 40 t/year for ADSs.

The requirements for the two scenarios presented above appear quite similar, with only the proportion of MOX/UOX fabrication capacities being notably different (1:10 and 1:1.77, correspondingly).

As a final consideration on the European Facility for Industrial Transmutation (EFIT) design, it should be mentioned that a transmuter of such a type might have benefits in regional scenarios. However, it would hardly be suitable for countries phasing out nuclear energy and implementing a partitioning and transmutation strategy in isolation. The plain reason for this is that transmutation addresses exclusively minor actinides and leaves most of the plutonium stocks unchanged.

The analysis performed in the PATEROS project for Scenarios 3 and 4 concluded that a regional approach with fast reactors used either as breeders or just as burners can make it possible to manage both plutonium and minor actinides originating from a number of countries. In this, the flexibility of a fast reactor providing for its easy conversion, at a desired point of time, from a breeder to burner and vice versa will be useful to reduce the radiotoxic HLW in both considered groups of countries. Moreover, the added value of the fast reactors compared to the ADS would be the electricity produced.

The ARCAS study [3.55] tries to address crucial issues in the partitioning and transmutation debate: which options are technologically feasible, and at what price. As a contractual service agreement project, it does not aim to perform R&D in the field, but rather to gather the available information and combine it in a global study. At the moment, the inventory and feedstock of minor actinides has been established and the reference fast reactor system and ADS have been defined. The fuel reprocessing and fuel fabrication facilities are being assessed and their choice finalized.

TABLE 3.24. PROPOSED REFERENCE MINOR ACTINIDE COMPOSITION

Nuclide	Content (%)
Am^{241}	39.55
Am^{242m}	0.22
Am^{243}	22.34
Np^{237}	32.91
Cm^{243}	0.059
Cm^{244}	3.97
Cm^{245}	0.95

Note: Minimum minor actinide annual stream (PATEROS scenario) is 2.3 t/year; maximum minor actinide annual stream (PATEROS extended to all European countries with present energy production) is 6.5 t/year.

TABLE 3.25. COMPARISON OF LWR, FR AND ADS COST ADVANTAGES AND DISADVANTAGES

	LWR	Fast reactor	ADS
Construction cost	+	−	−−
Operation and maintenance cost	+	−	−−
Fuel costs		+/−	−
MA transmutation capacity	−−	+	++

Note: ++ high advantages; + medium advantages; +/− both advantages and disadvantages; − medium disadvantages; −− high disadvantages.

The outcome of the simulations addressed the minor actinide streams (and their isotopic composition) evaluation from Group A (i.e. coming from a spent fuel storage after some decay time) and Group B (i.e. coming from a continuous feed from a PWR fleet) is shown in Table 3.24.[14]

Both fast reactors and ADSs have transmutation capabilities. As expected from their fuel loadings and spectra, the project work packages 2 and 3 have demonstrated that ADSs have a superior capability for transmutation compared to fast reactors. Furthermore, the required transport of spent fuel and dedicated burner fuel can be limited because of the high concentration of minor actinides in ADS fuel. The challenging question is whether these advantages could compensate for the extra difficulties and then costs of building these facilities. Table 3.25 shows the cost advantages and disadvantages for the three reactor systems considered.

3.3.1.5. Conclusions

With reasonable exploration of present technologies, partitioning and transmutation will allow largely reducing the long term burden of the spent fuel and HLW, and can thus contribute to significantly improving its management. Residual heat of HLW can be reduced though partitioning and transmutation of plutonium and minor actinides. This will make it possible to use galleries 3–6 times shorter in an underground geologic repository. In turn, this would help to reduce the footprint and the number of repository sites.

Transmutation can be accomplished efficiently either in ADSs or in fast reactors, or through a system based on a combination thereof. While dealing with HLW, the issue of ILW and, specifically, of the long lived ILW, should not be discarded as, with partitioning and transmutation in place, the radiotoxicity of such ILW would actually be definitive.

The PATEROS project concluded that regional strategies can provide a framework for implementation of innovative fuel cycles, with appropriate share of efforts and resources optimization. This project also outlined the ADS characteristics that would fit best to minor actinide transmutation in ‘double strata’ type scenarios.

The ADS was found mostly adapted to minor actinides and not transuranics. Therefore, the best mode of its application appears to be within a regional scenario where different countries would collaborate in the use of facilities, resources and inventories towards waste minimization. However, the same type of ADS will not be useful in the case of a country committed to a stagnant or decreasing use of nuclear energy that could decide to deploy partitioning and transmutation in ‘isolation’ for waste management.

Within the PATEROS project, it was also noted that implementation of partitioning and transmutation at a regional level (with a potential to reduce radiotoxicity of the disposed HLW below that of natural uranium ore after several hundreds of years) could be of benefit to all countries in the region (all 34 European countries) irrespective of which policy regarding nuclear each country is pursuing. It was also noted that regional partitioning and transmutation could perhaps even facilitate pro-nuclear decision making in some countries.

The ARCAS project tried to address crucial issues in the partitioning and transmutation debate: which options are technologically feasible and at what price. The final report summary[15] states that the ARCAS project has investigated:

> “The dependence of the economic performance of a transmutation facility from the electricity price.... If the electricity price is low, the economic performance of ADS–EFIT and EFR are comparable only for very good EFR transmutation performances, while for high electricity prices EFR is more convenient than ADS–EFIT. In case standard values are considered there is no net economical convenience in the adoption of one particular system.
>
> “When looking at the costs of electricity nuclear power plant fleets including FR and ADS respectively, the results of the comparison of these costs depend strongly on their relative costs. The increased costs of electricity produced by ADS may be balanced by its limited share in the energy mix and the bigger share of lower cost kW·h produced by LWR.”

[14] Further information is available at https://cordis.europa.eu/result/rcn/57137_en.html

[15] Available at https://cordis.europa.eu/result/rcn/57137_en.html

Determination of the break-even price of ADSs that would make the ADS scenario competitive compared to the fast reactor scenario was found to be a complex task [3.55]. Having in mind the very low level of readiness of key nuclear technologies addressed in ARCAS, the cost models used might not represent adequately the actual future costs of such technologies. In this context one could also note that ADSs are not being designed for electricity generation. This being said, electricity cost was found to be the only parameter to compare the different scenarios unambiguously. To make it work, the ARCAS concluded that:

> "one can consider the extra electricity cost for MA burning as the 'price' to be paid for minor actinide recycling and transmutation. The over-cost can then be viewed within the advantage of added sustainability of the closed fuel cycle, that recycles all its minor actinides, as well as from the viewpoint of reduction of long-lived nuclear waste."

3.3.2. Preliminary analysis of the nuclear energy development scenarios based on U–Pu multi-recycling in China

3.3.2.1. Introduction

As China seeks the rapid development of nuclear power, limited natural uranium resources will be one of its constraints [3.38, 3.57]. To address this problem, China has increased its uranium exploration and is also actively exploring the international uranium market. At the same time, China is seeking to implement a strategy for developing fast reactors and related closed nuclear fuel cycle infrastructure to ensure the sustainability of its large scale nuclear power development. A three step strategy has been adopted to develop this. The first step, which has already been realized, is to develop an experimental fast reactor. The China Experimental Fast Reactor (CEFR), a sodium cooled 65 MW(th) experimental fast reactor, has been operating since 2011. The second step is to develop a demonstration fast reactor with a 600 MW power capacity, while the third step is to develop commercial fast reactors with the capacity of 1000–1200 MW [3.58]. China has also decided to adopt a closed fuel cycle approach to sustain the development of fission energy.

This case study is associated with Task 1 of the SYNERGIES project. The objective of Task 1 is to evaluate the synergistic collaborative scenarios of fuel cycle infrastructure development. China expects to enable a significant growth of fast reactor capacity through a fast reactor centred scenario with reprocessing of PWR fuel. The complete case study can be found in Annex X on the CD-ROM accompanying this publication.

3.3.2.2. Objective and problem formulation

In order to accomplish the goal of nuclear power development, fast reactor technology needs to be developed. There are two types of fast reactor development scenarios. In the first type, there are sufficient uranium resources and the main task of fast reactors is to transmute minor actinides of PWR spent fuel. In the second type, there are not sufficient uranium resources and the main task of fast reactors is to breed and increase the capacity of nuclear power. This section focuses on the second type of fast reactor development scenario.

The mass flow of this NES in a closed nuclear fuel cycle is shown in Fig. 3.100. This case study presents and analyses the nuclear power scenarios in which the PWR–fast reactor is developed for a closed nuclear fuel cycle, based on the fast reactor centred scenario in order to preliminarily assess the potential of nuclear power development.

3.3.2.3. Assumptions, methods, codes and input data used

Research has shown that the population of China will increase to 1.43 billion by 2050. Primary energy consumption will be increased to 3.5 t standard coal equivalent (SCE)/year/person [3.59]. Total energy consumption will be 5 billion t SCE. The total electric capacity will be 2.5 billion kW. If the scale of Chinese nuclear power increases to 16% of total electricity capacity in 2050, which is the factor of the world average level at present, the capacity of nuclear power will be about 400 GW(e).

This section focuses on a nuclear power development scenario in which there are not sufficient uranium resources available. In order to accomplish the goal of nuclear power development under this scenario, fast reactors need to be developed. Cases of fast reactor and PWR matching development scenarios were analysed under

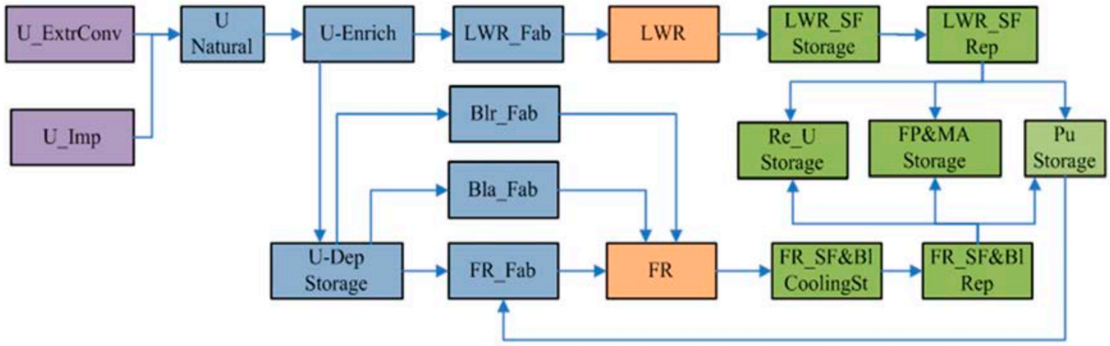


FIG. 3.100. Mass flow of the fast reactor centred scenario.

TABLE 3.26. CHINA SCENARIO STUDY CASES

	Case I	Case II	Case III	Case IV
Uranium resource (million t)	2.0	2.0	2.0	1.0
Matching strategy	PWR–FR(MOX)–FR(Metal)	PWR–FR(MOX)	PWR–FR(MOX)–FR(Metal)	PWR–FR(MOX)–FR(Metal)
PWR development goals	To 200 GW(e) in 2030	To 200 GW(e) in 2030	To 40GW(e) in 2020 To 70 GW(e) in 2030 To 90 GW(e) in 2040 To 200 GW(e) in 2050	To 40GW(e) in 2020 To 70 GW(e) in 2030 To 90 GW(e) in 2040 To 100 GW(e) in 2050

different constraints using the nuclear energy dynamic analysis code DESAE (Dynamic Energy System — Atomic Energy) [3.60], provided by the IAEA.

The CFR1000 is selected as the fast reactor model in this study. The CFR1000 is a Chinese designed innovative fast reactor concept which is a pool type SFR with 1000 MW(e). The core loads about 4.2 t of plutonium but can also support different fuel types. It operates on a one third refuelling scheme, with a refuelling cycle of 330 effective full power days. Using MOX fuel, the breeding ratio of the CFR1000 is 1.2, and about 1.5 when using metal fuel. These two SFRs are separately called FR(MOX) and FR(Metal). The PWR model is selected from advanced M310 based on the Daya Bay nuclear power plant. The planned operational lifespan for all nuclear power plants (PWR or fast reactor) is 60 years. The recycling time for both PWR spent fuel and fast reactor MOX spent fuel was supposed to be two years, which includes the time of intermediate storage, reprocessing and fuel fabrication. The time for this cycle is four years for FR(Metal). These estimates assume there is sufficient capacity to reprocess the spent fuel of every type of reactor and handle 1000 t HM per year.

The four resulting cases are analysed primarily according to the different supply of natural uranium resources and the development plans for the PWR and fast reactor. The list of cases is presented in Table 3.26. Cases I and II assume that the PWR nuclear power plants develop more quickly than in Cases III and IV. Cases III and IV are roughly based on the national development plan; different PWR capacities correspond to the different uranium resource supplies.

3.3.2.4. Summary presentation and analysis of the results

(a) Case I

Case I considers that the total availability of natural uranium is expected to be 2 million t, which should be the amount of fuel consumption for PWRs in the range of 200 GW(e) during their operating life. PWRs are expected to develop according to the maximum capacity supported by natural uranium resources. Fast reactor nuclear power plants with MOX fuel, FR(MOX), are assumed to achieve commercial operation by 2018; the scale increases by one reactor unit per year in the initial stage (2018–2020), and then depends on the cumulative amount of plutonium which is obtained from reprocessing of PWR and fast reactor spent fuel. The fast reactors with MOX fuel will no longer be developed after 2030. Fast reactors with metal fuel, FR(Metal), will be deployed instead, as quickly as possible. The results of calculations are shown in Figs 3.101–3.105. In Case I, the total consumption of natural uranium is 2.01 million t, and the development scale of PWR peaks at 200 GW(e) in 2030. In 2050, the total installed capacity of nuclear power is 360 GW(e), which includes 200 GW(e) from PWRs, 10 GW(e) from FR(MOX), and 150 GW(e) from FR(Metal). By 2050, 2300 t of PWR spent fuel are reprocessed, along with 300 t FR(MOX) spent fuel and 2700 t FR(Metal) spent fuel.

(b) Case II

In Case II, uranium resources and the PWR development plan are similar with the Case I. FR(MOX) is assumed to start operating from 2018, and the scale increase one reactor unit per year from 2018 to 2020; then fast reactors will develop as quickly as possible, according to the cumulative amount of plutonium obtained from reprocessing PWR and fast reactor spent fuel. The difference from Case I is the assumption that FR(Metal) will not be developed. The calculated results are shown in Figs 3.106–3.110. In Case II, the total consumption of natural uranium is also 2.01 million t as in Case I. In 2050, the total installed capacity of nuclear power is 257 GW(e), which include 200 GW(e) from PWR and 57 GW(e) from FR(MOX). By 2050, 2300 t of PWR spent fuel are reprocessed, along with corresponding 1100 t of FR(MOX) spent fuel.

(c) Case III

This case also assumes the availability of natural uranium resources and the same fast reactor development plan as in Case I. FR(MOX) is assumed to start operating from 2018, and FR(Metal) is planned for 2030. The difference from Case I assumptions is in the development scale for PWR that increases to 40 GW(e) by 2020, to 70 GW(e) by 2030, to 90 GW(e) by 2040 and to 200 GW(e) by 2050. The calculated results are shown in Figs 3.111–3.115. In Case III, the total consumption of natural uranium is 1.98 million t, and the development scale of PWRs peaks at 200 GW(e) in 2050. In 2050, the total installed capacity of nuclear power is 303 GW(e), which includes 200 GW(e) from PWR, 10 GW(e) from FR(MOX), and 93 GW(e) from FR(Metal). By 2050, about 2200 t of PWR spent fuel are reprocessed, along with corresponding 300 t FR(MOX) spent fuel and 1700 t FR(Metal) spent fuel.

(d) Case IV

Case IV is very similar to Case III, except that only 1 million t of natural uranium resources are available. The calculated results are shown in Figs 3.116–3.120. In Case IV, the total consumption of natural uranium is 1.01 million t, and the development scale of PWRs peaks at 100 GW(e) in 2050. In 2050, the total installed capacity of nuclear power is 163 GW(e), which includes 100 GW(e) from PWR, 6 GW(e) from FR(MOX) and 57 GW(e) from FR(Metal). By 2050, about 1100 t of PWR spent fuel are reprocessed, along with corresponding 200 t of FR(MOX) spent fuel and 1000 t of FR(Metal) spent fuel.

If a comparison between the four defined cases is performed, Case I is closest to the desired scale of the nuclear power (about 400 GW(e)).

3.3.2.5. Conclusions

China is devoted to the peaceful use of nuclear energy to meet growing national energy demand. The proper number of nuclear power plants can provide clean energy with low risk, which is essential to ensure that modern industrial civilization can be enjoyed with as little damage as possible to the environment.

The fast reactor is a promising technology to ensure the sustainable development of nuclear energy based on the capability to produce new fuel from depleted uranium and simultaneously to burn the long life radioactive waste. SFR technology is one of the six recommended Generation IV technologies, with inherent safety features. It is anticipated that the fast reactors will provide people with sufficient clean power for the long term future.

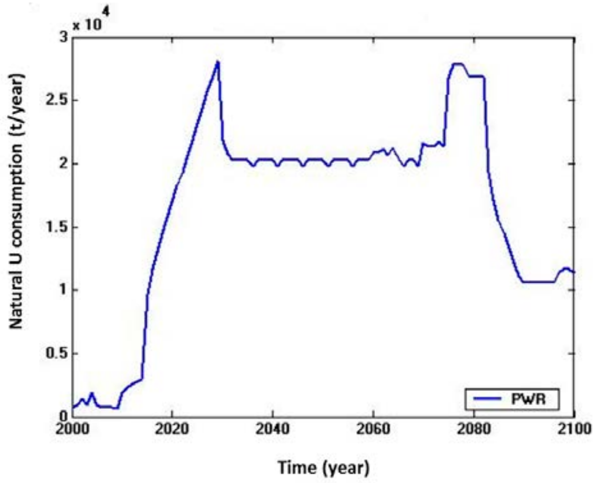


FIG. 3.101. Annual consumption of natural uranium for Case I.

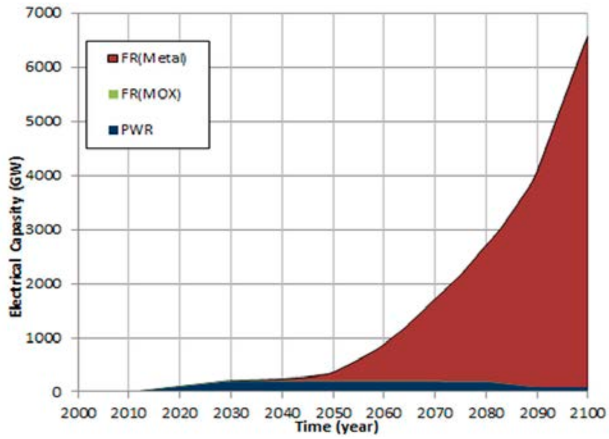


FIG. 3.102. Total development scale of installed capacity for Case I.

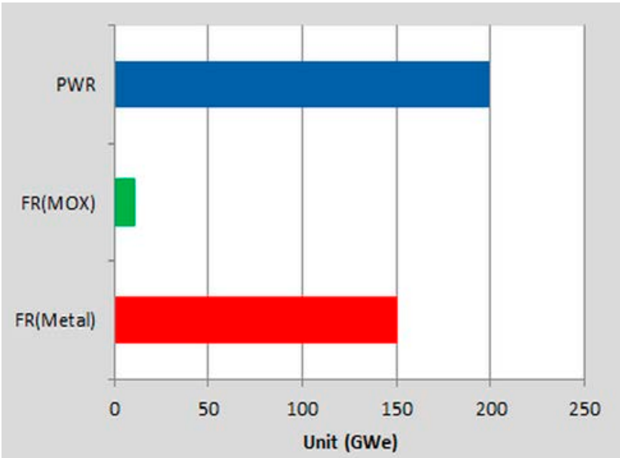


FIG. 3.103. Nuclear power scale for each type of nuclear power plant in 2050 for Case I.

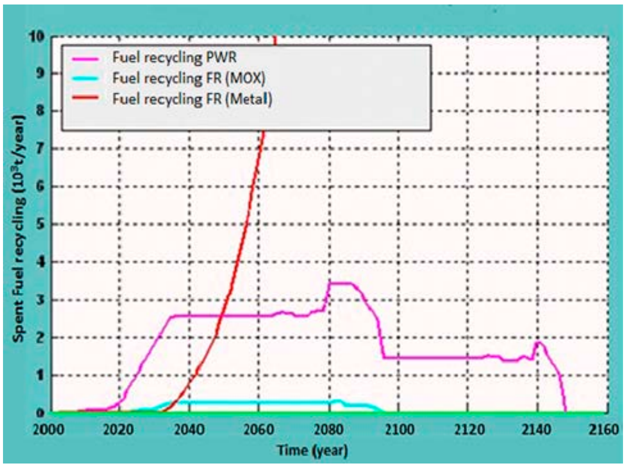


FIG. 3.104. Reprocessing demand for Case I.

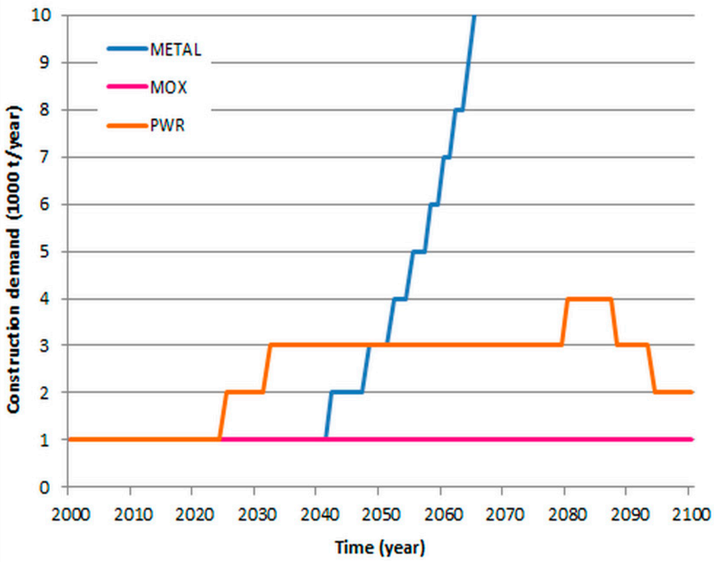


FIG. 3.105. Reprocessing plant construction demand for Case I.

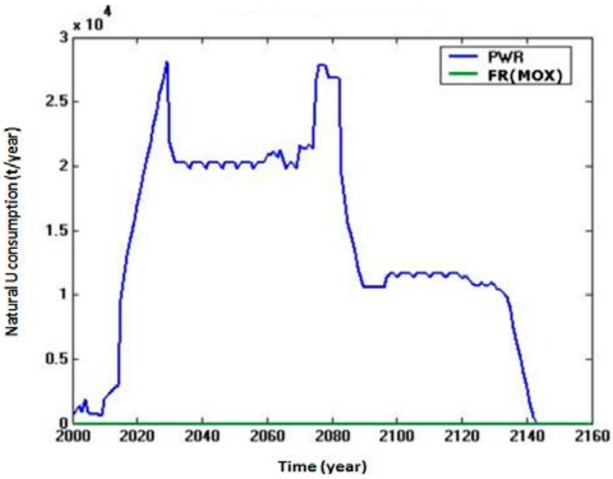


FIG. 3.106. Annual consumption of natural uranium for Case II.

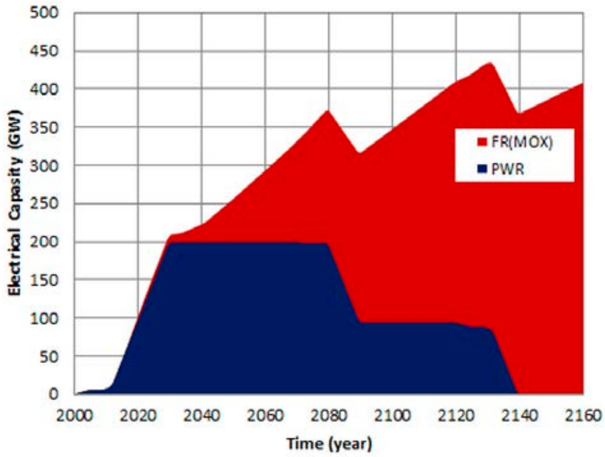


FIG. 3.107. Total development scale of installed capacity for Case II.

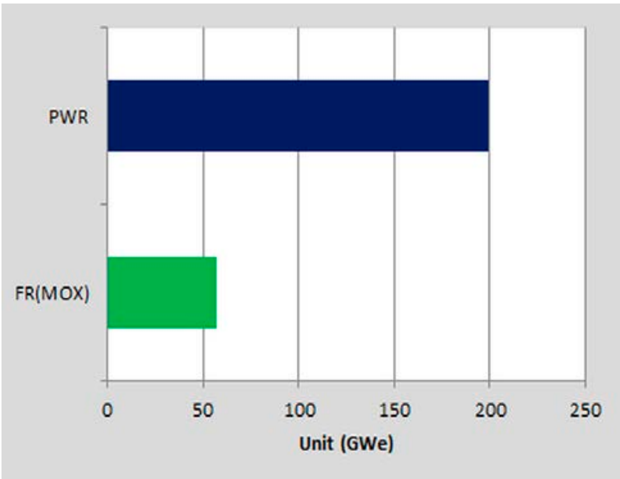


FIG. 3.108. Nuclear power scale for each type of nuclear power plant in 2050 for Case II.

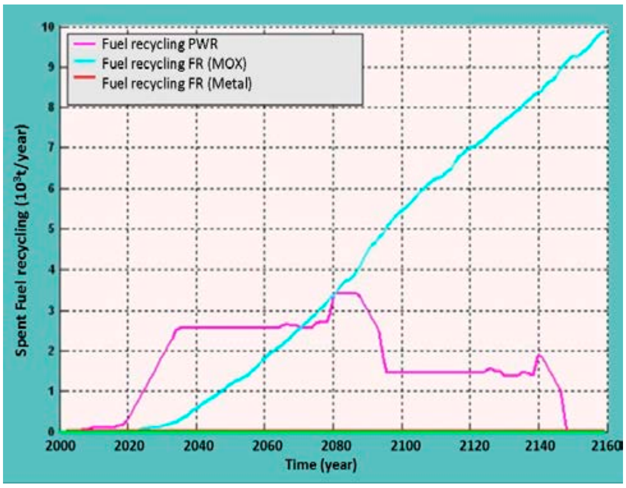


FIG. 3.109. Reprocessing demand for Case II.

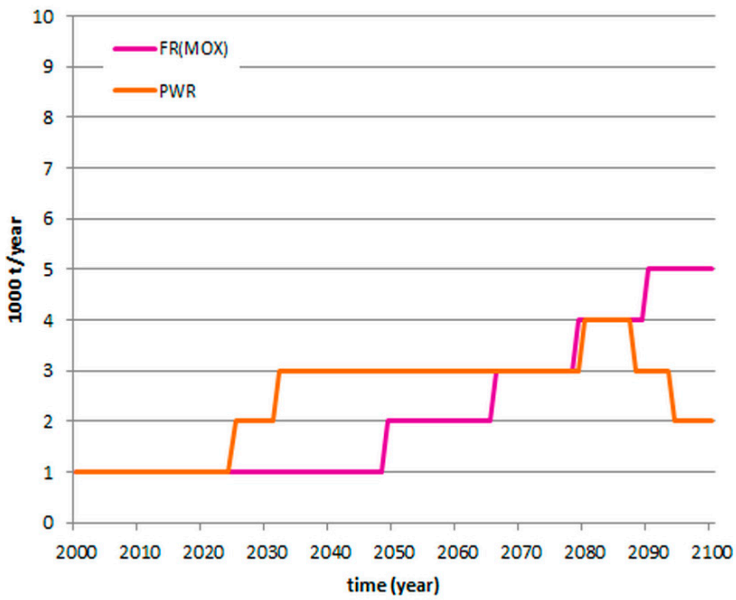
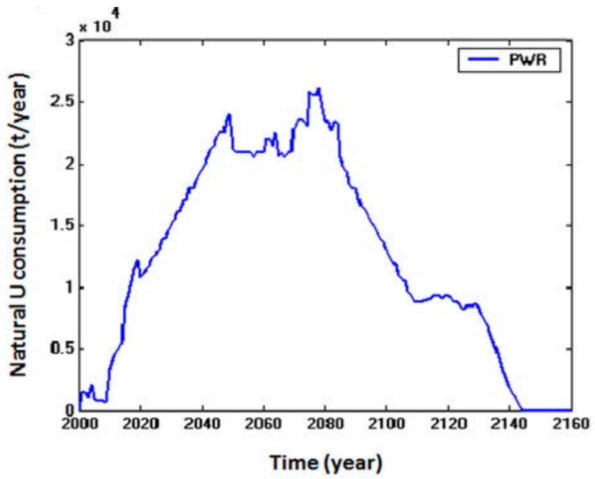


FIG. 3.110. Reprocessing plant construction demand for Case II.



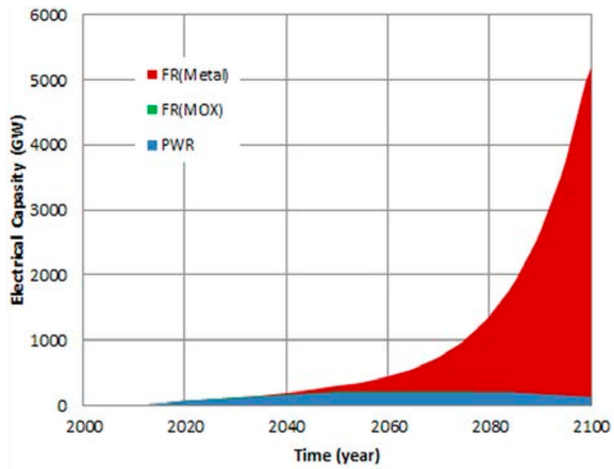
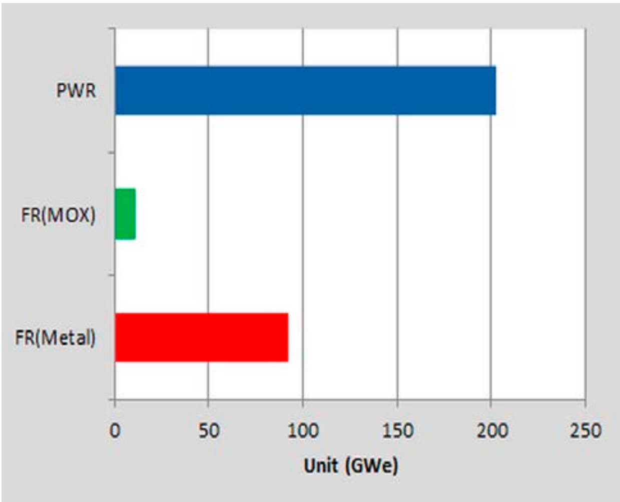


FIG. 3.111. Annual consumption of natural uranium for Case III.

FIG. 3.112. Total development scale of installed capacity for Case III.



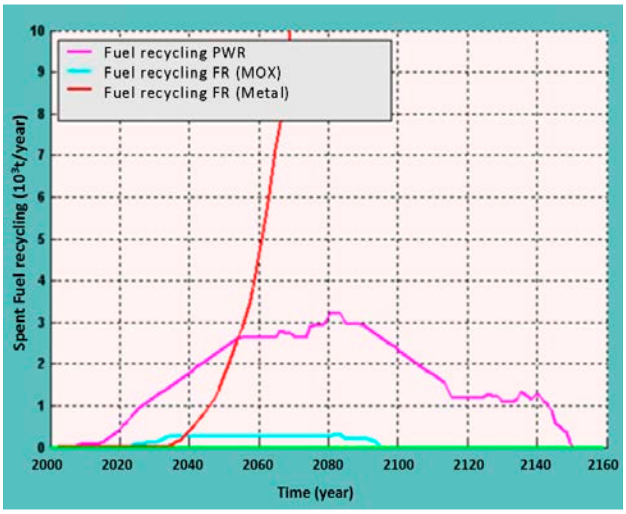


FIG. 3.113. Nuclear power scale for each type of nuclear power plant in 2050 for Case III.

FIG. 3.114. Reprocessing demand for Case III.

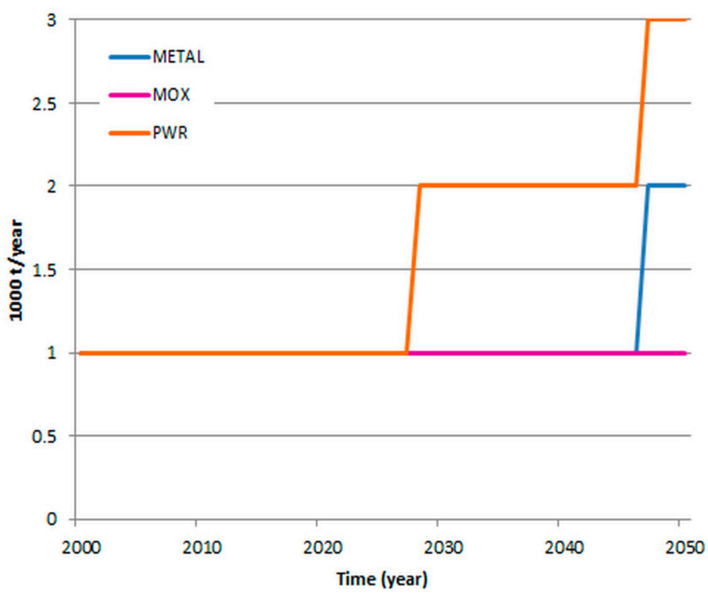


FIG. 3.115. Reprocessing plant construction demand for Case III.

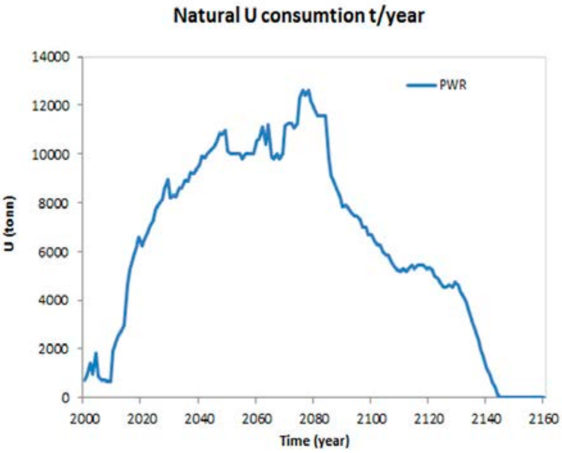


FIG. 3.116. Annual consumption of natural uranium for Case IV.

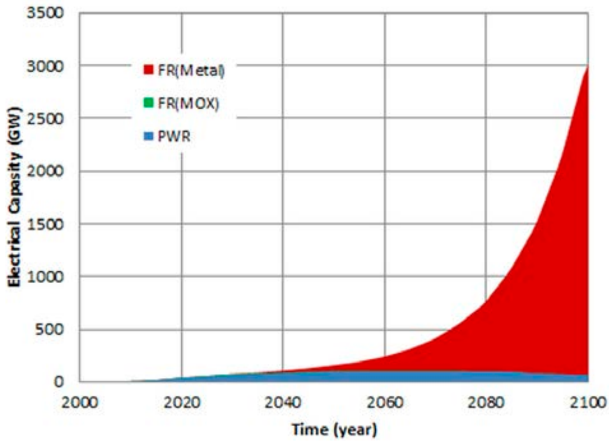


FIG. 3.117. Total development scale of installed capacity for Case IV.

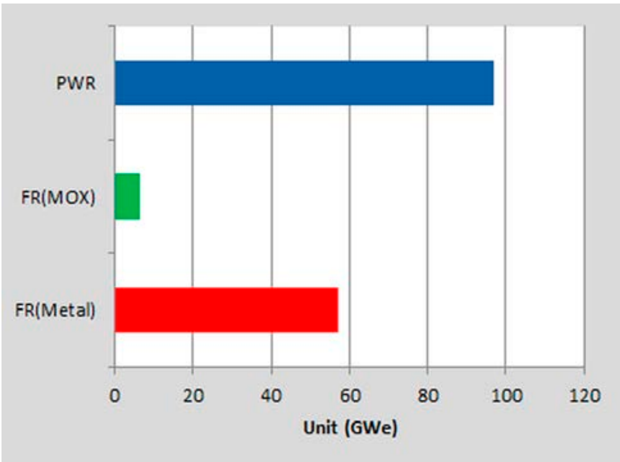


FIG. 3.118. Nuclear power scale for each type of nuclear power plant in 2050 for Case IV.

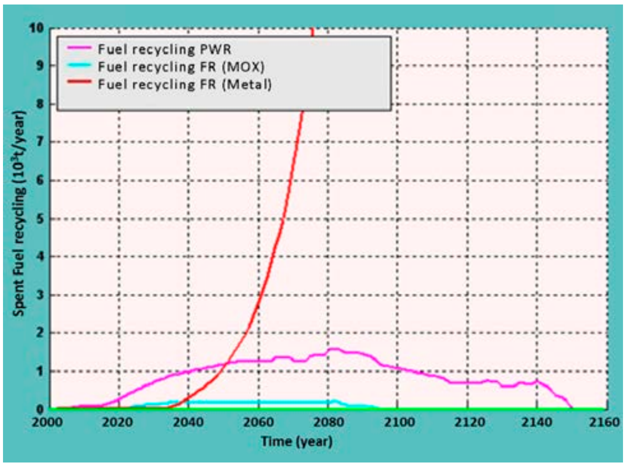


FIG. 3.119. Reprocessing demand for Case IV.

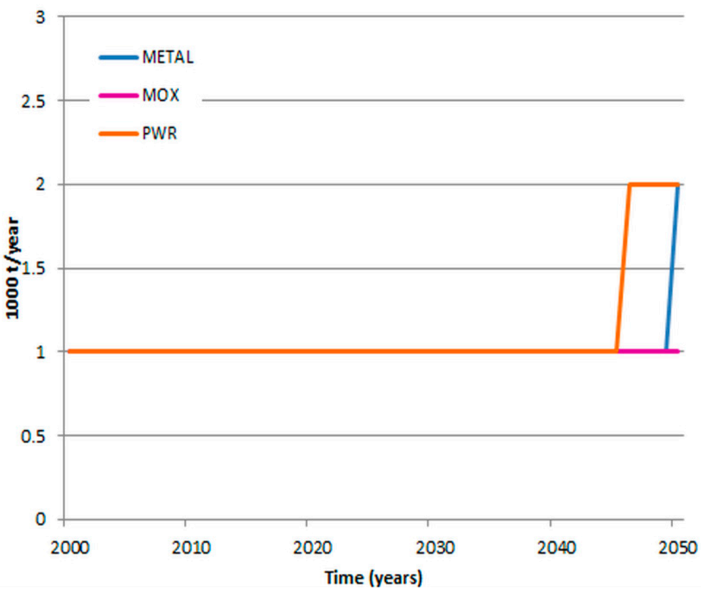


FIG. 3.120. Reprocessing plant construction demand for Case IV.

Development of fast reactors and PWRs in China is very important for the large scale sustainable development of nuclear energy. To achieve faster development of the nuclear power capacity, it is necessary to have sufficient natural uranium resources to support the large scale development of PWR nuclear power plants, and as the result, to accumulate enough plutonium from spent fuel reprocessing to load fast reactor cores, which is a prerequisite for the rapid development of fast reactors. The large scale development of fast reactors requires sufficient reprocessing capacity. On the other hand, R&D on the metal fuel for fast reactors with high breeding ratios and the advanced reprocessing technology can shorten the time needed for reprocessing and increase the installed capacity.

China conducts independently R&D on nuclear energy technology to increase the nuclear power share, but also needs to cooperate with the international community on uranium resources availability and fast reactor and reprocessing technologies.

3.3.3. Studies of minor actinide transmutation in SFRs

3.3.3.1. Introduction

Minor actinides have high radiotoxicity and lifetimes of hundreds of thousands of years. Some of them are fissile materials or fertile materials from which fissile materials could be bred. Minor actinides create additional burden on repositories by producing heat. Minor actinide management is considered important because it could reduce engineering complexities on a final repository of nuclear waste and uncertainties in long term performance of repositories, although repositories could be designed to avoid migration and release of minor actinides in the long term.

A partitioning and transmutation strategy can be utilized to reduce the amount of minor actinides. In partitioning and transmutation, long lived minor actinides are separated from HLW and then transmuted in reactors to change them into stable or relatively short lived nuclides.

Options to incinerate minor actinides are under investigation, including adding them to fuel of thermal or fast reactors as well burning them in dedicated transmutation systems, such as a fast burner reactor, ADS or molten salt reactor. The SFR is currently the most realistic and effective transmutation reactor, as it features a hard neutron spectrum and high flux level, and also has gained a lot of engineering experience worldwide.

Many previous studies have considered minor actinide transmutation in SFRs, including homogenous transmutation by adding minor actinides in SFRs homogenously as well as heterogeneous transmutation by setting dedicated targets containing minor actinides into the SFR core and burning in a dedicated SFR burner. The main result obtained is that the amount of minor actinides in the core cannot be too large, otherwise reactor core neutronics performance will be significantly affected which in turn would increase the cost of reactor safety. For a SFR minor actinide burner, the neutronics performance is degraded greatly compared to typical SFRs or SFRs with a small amount of minor actinides in addition to fuel, although in burners the minor actinide incineration effect is better.

In this section, two approaches to minor actinide transmutation in SFRs are studied: multi-recycling transuranic in SFRs, and a dedicated SFR minor actinide burner. The reactor core neutronics performance and minor actinide transmutation and incineration effects are analysed. The results from this study could be used as the input for scenario analyses.

This section is connected to Task 3 of the SYNERGIES project. The objective of Task 3 is to examine how NESs (including reactors and nuclear fuel cycles) could take advantage of the emerging dedicated transmutation systems or purposeful minor actinide applications in creation of a synergistic sustainable nuclear architecture. The complete case study can be found in Annex XXVI accompanying this publication.

3.3.3.2. Objective and problem formulation

As mentioned above, there are different options to transmute minor actinides, such as adding them into fuel in thermal or fast power reactors, or burning them in dedicated burner reactors. To meet the objective of Task 3 in the SYNERGIES project, the objective of the study presented here is to determine the better way to transmute minor actinides in SFRs between transuranic multi-recycling and dedicated burner, from the viewpoint of reactor core neutronics performance and minor actinide transmutation effect.

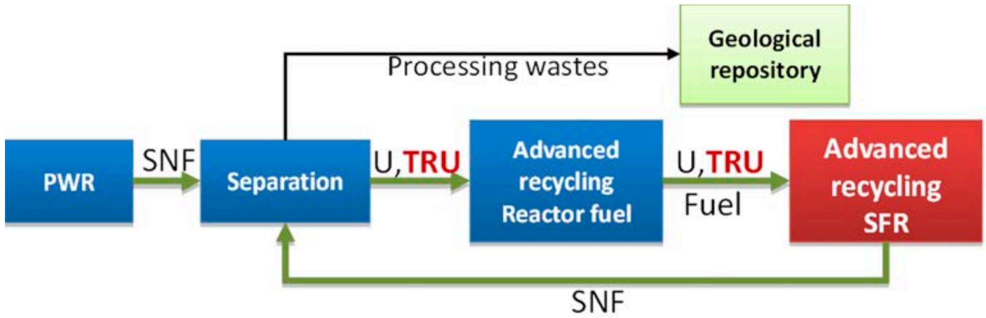


FIG. 3.121. Fuel cycle schematic diagram for transuranic multi-recycling in sodium cooled fast reactors.

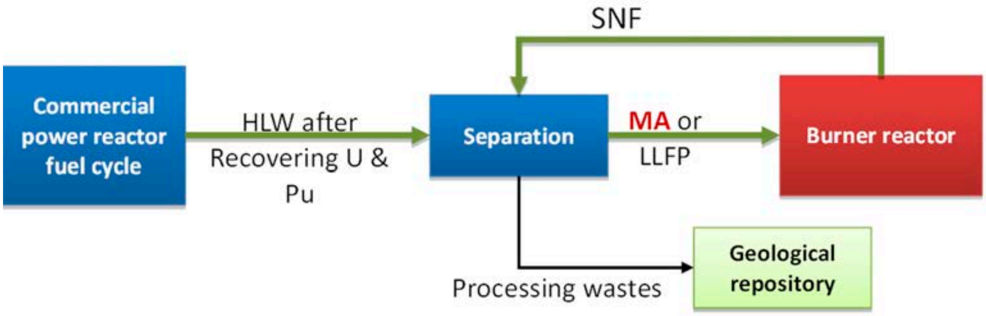


FIG. 3.122. Fuel cycle schematic diagram for dedicated minor actinide burners.

The first one — transuranic multi-recycling — involves putting plutonium mixed with minor actinides as transuranic, which is reprocessed from PWR spent fuel into SFR fuel; the transuranic will then be multi-recycled to transmute minor actinides contained. The second approach is to use a specially designed burner SFR to transmute minor actinides while keeping the ratio of minor actinides in the fuel under 5% to prevent degradation of core neutronics performance. In this section, the results of the two approaches previously mentioned, including the minor actinide transmutation effect and its influence on core neutronics performance, are studied and compared. The fuel cycle schematic diagrams are shown in Figs 3.121 and 3.122.

3.3.3.3. Assumptions, methods, codes and input data used

(a) Sodium cooled fast reactor core description

The reference reactor core for this analysis is the 800 MW(e) SFR, with a thermal power of 2100 MW, designed by the China Institute of Atomic Energy (CIAE) [3.61, 3.62]. The reactor core is similar to the Russian BN-800 [3.63], except for an additional radial blanket row and extended cycle time from 140 to 160 days. General parameters of in-core subassemblies such as fuel subassemblies, control rods, reflector and shielding subassemblies are the same as those of BN-800 core. The core uses MOX fuel, in which heavy metal is composed of depleted uranium and industrial plutonium from PWR spent fuel, with burnup ratio of 45 GW·d/t U. The considered isotopic composition of plutonium is the following: $^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$ = 0.009/0.615/0.220/0.119/0.041wt%.

A one third core refuelling scheme is adopted, which means that fuel subassemblies will stay in the core for three cycles with total irradiation time of 480 days. The average fuel discharge burnup is 73.5 GW·d/t HM, with the maximum burnup of 111.4 GW·d/t HM. The blanket subassemblies will stay in the core for four cycles, or 640 days

(b) Computation tools

The computation tools include two categories: criticality calculations and burnup calculations. The tools used for criticality calculation include the CITATION code [3.64] and the PASC-1 code [3.65], which generates the few groups data library for the CITATION code. For isotopic burnup calculations, the ORIGEN code [3.66] was used, being capable to analyse the composition change of transuranics when multi-recycled.

The fine 171 groups NVitamin-C library was used as the source library. This library is an updated version of the Vitamin-C library and was developed by the Nuclear Data Center of the CIAE based on the evaluated nuclear data libraries ENDF/B-VI, JEF-2, CENDL-2 and JENDL-3.

Full core 3-D diffusion calculations, including steady state, burnup and perturbation calculations, were performed using the CITATION code, which is widely used in-reactor core neutronics analysis and was proven to be reliable.

The few groups microscopic cross-section library prepared for the CITATION code is generated by the PASC-1 code system for the specific core layout geometry. The CITATION cross-section library can be processed by a variety of ways, but the XSDRN code [3.67] (1 D SN transport code in the PASC-1 code system) is specifically designed for this purpose. PASC-1 is a code package for condensing multi-group cross-sections into few groups and is similar to AMPX.

Finally, equilibrium composition analysis of transuranics was performed and some associated parameters of transuranic multi-recycling, such as transuranic radioactivity and thermal power, were obtained by using the ORIGEN code developed for isotopic burnup and decay analysis in nuclear fuel cycle processes. It is worth noting that single group cross-sections used in the ORIGEN code (i.e. 302 lib in ORIGEN input data) are updated with the actual neutron spectrum of a reference core, which means that the reference core neutron spectrum is used to condense a new 302 lib for the ORIGEN code.

3.3.3.4. Summary presentation and analysis of the results

(a) Transuranic multi-recycling in reference sodium cooled fast reactor core [3.68]

Table 3.27 presents the core initial heavy metal loading for the reference core and the transuranic recycling core. Compared to the reference core, the minor actinide loading mass in the transuranic fuelled core increases from 0 to 310.3 kg, and the uranium loading mass decreases by about 310.1 kg, while the plutonium loading mass keeps unchanged.

The calculation results of core safety and kinetic parameters in the beginning of cycle (BOC) at equilibrium state are presented in Table 3.28. Compared to the reference core, the impacts on core performance caused by changing driving fuel from plutonium to transuranics are negligible in spite of the lower minor actinide weight percentage in transuranics, except for the sodium void worth. Sodium void worth is positive in both cores and increases by 45.0% in transuranic fuelled core.

When transuranics are multi-recycled, the characteristics of transuranic composition are different for the two fuel types, as shown in Fig. 3.123 for minor actinides and plutonium weight percentage, and in Fig. 3.124 for the weight percentage of different minor actinide elements (neptunium, americium and curium) in transuranics. In both figures, the vertical axis represents weight percentage and the horizontal axis represents total transuranic recycle times. In each cycle the fuel will be irradiated to a burnup rate of 70 MW·d/kg.

Results from Fig. 3.124 indicate that the minor actinide fraction decreases more quickly in metal fuel, and is lower than that in MOX fuel. If transuranics are recycled, in the reference core (MOX fuel) minor actinide percentage in the transuranics will first decrease to around 7.24% (minimum) within 8 transuranic recycles and then will slowly increase to around 7.7% after 20 transuranic recycles. The increase of the minor actinide fraction is mainly caused by curium accumulating in MOX fuel. However, in the case of metal fuel, the equilibrium state for minor actinide fraction will be achieved after about 15 transuranic recycles, and the equilibrium percentage is about 3.8%. Once the equilibrium state in metal fuel is realized, the minor actinide percentage in transuranics will be stable and is considerably lower than the minor actinide percentage in PWR spent fuel; this means the minor actinide inventory is effectively controlled. Such performance demonstrates a better minor actinide transmutation effect for metal fuel compared to MOX fuel.

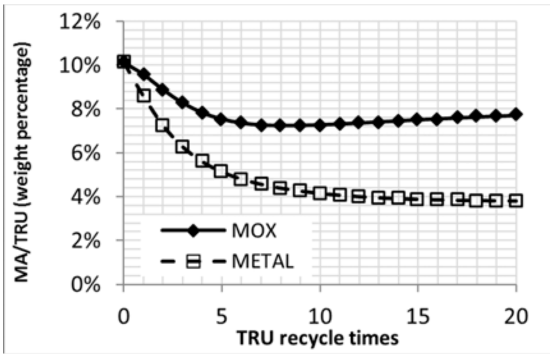
TABLE 3.27. CORE INITIAL LOADING

	Reference core	Reference core fuelled with transuranics
Fuel composition	(Pu, U) O_2	(TRU, U) O_2
Core initial loading (kg)		
U	9887.2	9577.1
Pu	2757.1	2757.1
Minor actinides	0	310.3

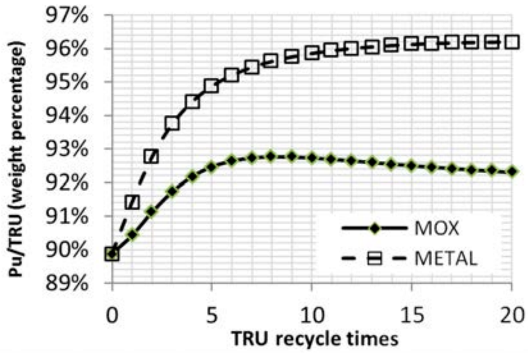
TABLE 3.28. SAFETY AND KINETIC PARAMETERS IN BOC AT EQUILIBRIUM STATE

	β_{eff} (pcm)	$\Delta\rho_{burnup}$ (\$)	K_D[1] (pcm)	Sodium void worth[2] (\$)
Reference core	382	9.47	−793	2.25
Reference core fuelled with transuranics	372	8.24	−666	3.27

[1] Doppler constant is used to evaluate Doppler feedback reactivity when fuel average temperature increases from $T1$ to $T2$, $\Delta\rho = K_D \cdot \ln(T2/T1)$.
[2] Assumed sodium voiding only in-core zone.

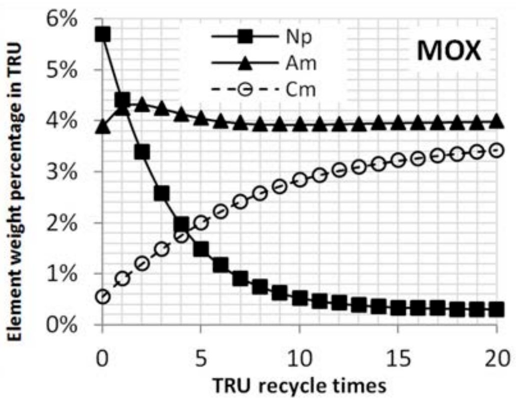


(a)

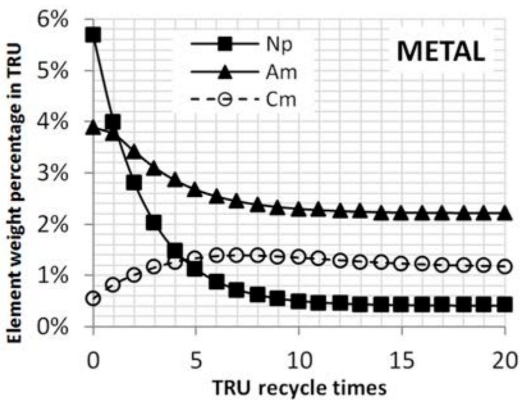


(b)

FIG. 3.123. Minor actinide (a) and plutonium (b) weight percentage in transuranics when transuranics are multi-recycled.



(a) Mixed oxide fuel



(b) Metal fuel

FIG. 3.124. Element weight percentage in transuranic when it is multi-recycled.

For minor actinide element composition Fig. 3.124 shows that the neptunium equilibrium percentage in transuranics is similar for the two considered fuel types, while different for americium and curium. When using metal fuel, the americium and curium weight percentage is considerably lower than for the case when using MOX fuel, especially for curium (a high atomic number element with high heat and neutron emission). The percentage increases first and then decreases gradually after the transuranics has been recycled for 7 times in the metal fuel core, while in the MOX fuel core, curium percentage increases continuously and cannot achieve equilibrium state even after 20 transuranic recycle times. If the transuranics are recycled for many times, the percentage of americium and curium in the transuranics in the MOX fuel will be much higher than the one in the metal fuel. For example, after 10 transuranic recycles, the americium fraction in the transuranics is about 3.9% for MOX fuel and about 2.3% for metal fuel, while the curium fraction is about 2.8% for MOX fuel (still increasing) and 1.3% for metal fuel (starting to decrease slowly). The reason for this difference is mainly due to the neutron spectrum in the metal fuelled core being harder than that in the MOX fuelled core. For the main minor actinide nuclides, a harder neutron spectrum will always bring a larger ratio of fission/capture cross-sections, which means there is a greater chance of fission reaction and a smaller chance of capture reaction; this further leads to less production of americium and curium for metal fuel.

In addition, whether in MOX or metal fuel, after the transuranics have been recycled for 5–6 cycles, the equilibrium state of plutonium composition will be realized (see Fig. 3.125), which shows a change of plutonium isotopic composition when multi-recycling. For different fuel types, however, the equilibrium percentage of fissile plutonium isotopes is different. Due to high mass density (high atomic density for heavy metal nuclides) and hard neutron spectrum, the conversion effect of ^{238}U to ^{239}Pu in metal fuel core is higher than that in MOX fuel core. Therefore, for metal fuel the equilibrium fraction of ^{239}Pu + ^{241}Pu in plutonium is about 64%, while for MOX fuel a smaller fraction about 54% is obtained.

(b) Minor actinide burner reactor [3.69]

First, considering preliminarily safety parameter limits, the design objective for the minor actinide burner reactor core is set as oxide fuel, with conventional fuel subassembly structure and fuel composition, linear power density lower than 48 kW/m, sodium void reactivity lower than +5$, and whole core minor actinide fission fraction larger than 10% (supporting ratio of minor actinide incineration > 6).

Table 3.29 gives reactor power, the PuO_2 percentage in fuel, and heavy mass load in different minor actinide burner cores, which are studied as different cases. In this study, two categories of core layout (traditional cylindrical core and annular core, respectively) and a total of four different cases are studied to compare neutronics properties, including (see Fig. 3.126 for the core layout):

(i) Case C1, traditional cylindrical core with 20wt% minor actinide addition in three fuel zones.
(ii) Case C2, traditional cylindrical core with 20wt% minor actinide addition in middle and outer fuel zones, but no minor actinide addition in inner fuel zone with high sodium reactivity worth, so as to reduce sodium void

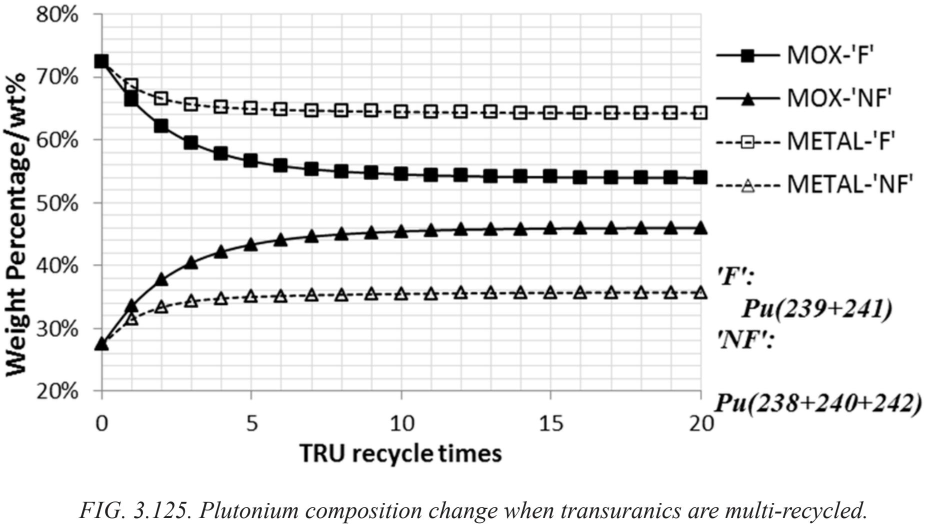
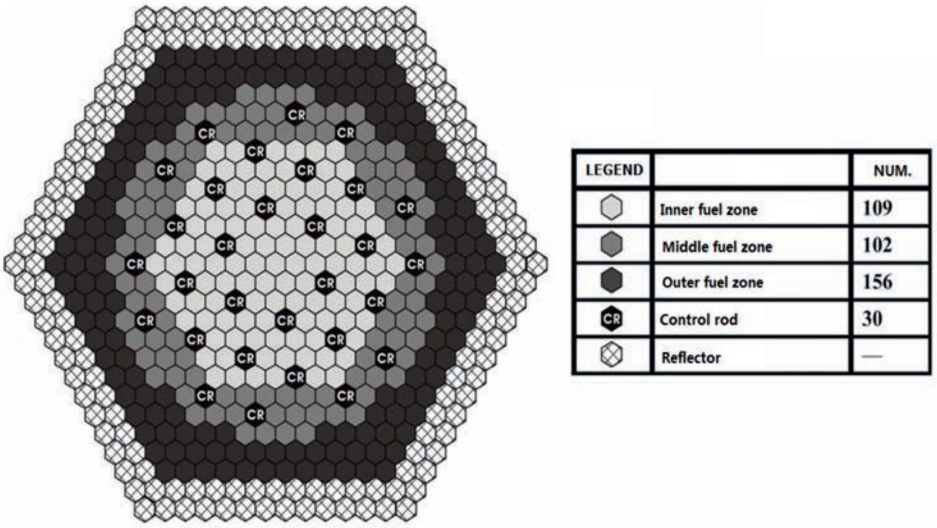


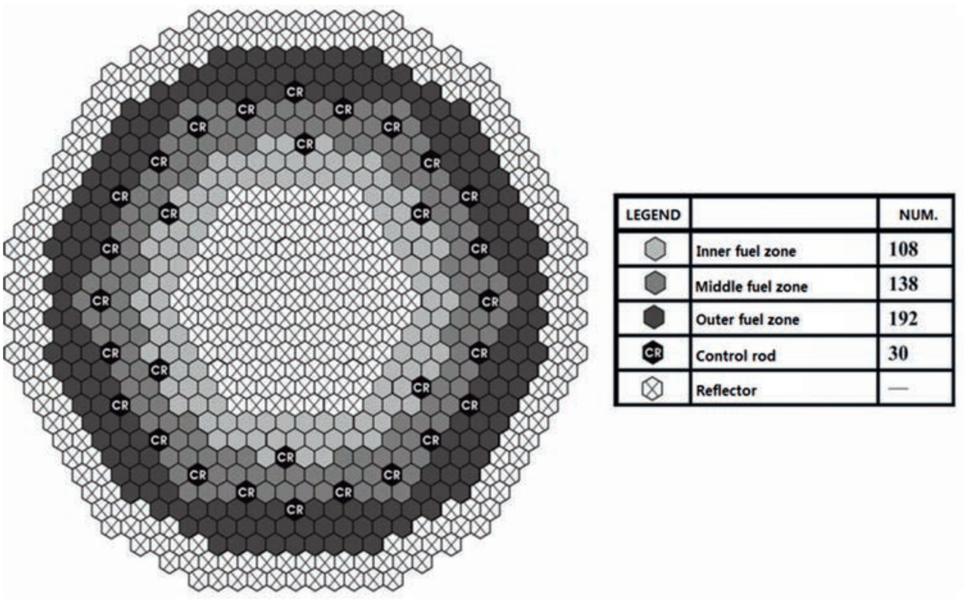
FIG. 3.125. Plutonium composition change when transuranics are multi-recycled.

TABLE 3.29. HEAVY METAL LOADING IN DIFFERENT CASES

	C1	C2	C3	C4
Power level (MW(th))	1120	1000	1300	1240
PuO_2 percentage (wt%) (inner/middle/outer zone)	21.8/24.7/27.6	23.8/25.6/28.9	27.4/25.3/29.4	25.7/28.7/29.7
HM loading (kg)				
U	3692.5	3998.8	4205.7	4572.8
Pu	1669.8	1761.6	2194.2	2211.9
Minor actinides	1340.7	942.6	1600.1	1096.0
Fissile material specific loading mass (kg/MW(th))	1.501	1.774	1.698	1.795



(a) Traditional core



(b) Annular core

FIG. 3.126. Minor actinide burner reactor core layout.

reactivity and to enhance Doppler feedback in inner fuel zone. Meanwhile, absorber layer is set under active zone to increase axial leakage and then reduce sodium void reactivity.

(iii) Case C3, annular core with 20wt% minor actinide addition in three fuel zones.

(iv) Case C4, annular core with 20wt% minor actinide addition in inner and outer fuel zones, but no minor actinide addition in middle fuel zone with high sodium reactivity worth, so as to reduce sodium void reactivity and to enhance Doppler feedback in middle fuel zone.

Table 3.30 gives some core neutronics parameters in C1–C4 cores. In C1 and C3 cores, because all of three fuel zones contain 20wt% minor actinides, the whole core minor actinide fission fraction is very high, reaching 19.6% and 18.3%, respectively. However, high minor actinide fission fraction brings several problems, such as β_{eff} dropping to less than 300 pcm, 297.1 pcm and 295.9 pcm, respectively in C1 and C3 cores. The negative Doppler feedback is also weak, with the Doppler constant K_D only reaching −105.8 pcm and −124.9 pcm, respectively; while sodium void reactivity increases significantly, reaching +8.2$ and +6.1$, respectively.

In C2 and C4 cores, because there are no added minor actinides in the inner fuel zone (C2 core) and the middle fuel zone (C4 core) — due to high sodium reactivity values and the placing of a neutron absorber layer under the core active zone in the C2 core to increase axial neutron leakage — the sodium void reactivity is greatly reduced to +3.9$ in the C2 core and +3.0$ in the C4 core, both below the design objective of less than +5$. In the reference core (with standard MOX fuel), the sodium void reactivity is +2.3$, and reaches +4.3$ after an addition of 5wt% minor actinides in the fuel. On the other hand, compared to C1 and C3 cores, since minor actinide loading mass is reduced, the whole core minor actinide fission fraction is decreased to 12.5% and 11.9% for the C2 and C4 cores, respectively, and both achieve the design objective of it being larger than 10%. In addition, the burnup reactivity loss of the C2 and C4 cores is respectively increased to 9.9$ and 11.5$, compared to 9.5$ in the reference core. The Doppler feedback is also reduced, reaching only about 30% of reference core, K_D being −240.1 pcm and −241.8 pcm, respectively.

The fissile nuclide conversion ratio in the C1–C4 cores is reduced significantly to between 0.4 and 0.5 as a result of the lack of a blanket zone and the high minor actinide percentage in fuel. As the C1–C4 cores are designed to be minor actinide burners, the lower conversion ratio accords with the design objective.

Table 3.31 gives minor actinide transmutation effects, which means minor actinide net consumption, including converting to other actinides by capture reaction, while setting standard core with 5wt% minor actinide addition as reference. In the minor actinide burner, due to increasing neutron leakage, minor actinide transmutation rate is reduced, but net minor actinide disappearance is larger, since minor actinide loading is increased.

It is known that for reducing long term radiotoxicity, minor actinide disappearance by fission reaction, referred to as minor actinide incineration, is more important than that by capture reaction. Two parameters, specific consumption by incineration and incineration rate, are used to compare minor actinide incineration effect in the burner with the reference core. The minor actinide specific consumption by incineration means the mass of minor actinide fissioned normalized to per unit power output; and minor actinide incineration rate means the mass ratio of minor actinide fissioned to minor actinide loading. Table 3.32 presents fuel burnup and minor actinide incineration effect in the C1–C4 cores, while also setting standard core with 5wt% minor actinide addition into the fuel heavy metal as the reference core.

TABLE 3.30. CORE PARAMETERS FOR DIFFERENT CORES

	Reference core	Reference core with 5wt% minor actinides in fuel	C1	C2	C3	C4
Minor actinide fission fraction (%)	—	5.5	19.6	12.5	18.3	11.9
β_{eff} (pcm)	381.8	369.3	297.1	323.0	295.9	320.3
$\Delta\rho_{\text{burnup}}$ ($)	9.5	7.4	8.1	9.9	9.4	11.5
Sodium void reactivity ($)	2.3	4.3	8.2	3.9	6.1	3.0
K_D (pcm)	−793.0	−538.7	−105.8	−240.1	−124.9	−241.8
Conversion ratio	1.046	0.992	0.465	0.483	0.401	0.439

TABLE 3.31. MINOR ACTINIDE TRANSMUTATION EFFECT IN THE BURNER CORE

	Reference core with 5wt% minor actinides	C1	C2	C3	C4
Minor actinide loading mass (kg)	632.3	1340.7	942.5	1600.1	1096.0
Minor actinide transmutation ratio* (%)	8.333	7.605	6.032	6.835	6.517
Specific support ratio by minor actinide transmutation (kg/GW(th)·year)	57.9	207.7	129.7	191.9	125.3

* Minor actinide net consumption over fuel lifetime, including conversion to other actinides by capture reaction, as fraction of the initial content of the minor actinides.

TABLE 3.32. MINOR ACTINIDE INCINERATION EFFECT IN THE BURNER CORE

	Reference core with 5wt% minor actinides	C1	C2	C3	C4
Minor actinide loading mass (kg)	632.3	1340.7	942.5	1600.1	1096.0
Av. fuel burnup (GW·d/t)	73.9	80.2	70.8	78.0	73.0
Minor actinide incineration rate (%)	2.93	2.67	2.16	2.43	2.19
Minor actinide fission fraction (%)	5.5	19.6	12.5	18.3	11.9
Minor actinide specific consumption by incineration (kg/GW(th)year)	20.4	73.0	46.4	68.4	44.1
Supporting ratio of minor actinide incineration	3.1	11.1	7.0	10.4	6.7

The calculation results show that fuel burnup is similar to reference core, which is among 70.8–80.2 GW·d/t HM, but the plutonium fraction in the heavy metal is increased in burner as neutron leakage increased; thus, the minor actinide incineration rate in burner is reduced when compared to reference core. On the other hand, since the fraction of minor actinide fission in the burner is higher than that in reference core, the specific consumption of minor actinides by incineration is greater than that in reference core, which leads the supporting ratio of minor actinide incineration reaching 7.0 and 6.7 in the C2 and C4 cores, respectively, and that is only 3.1 in the reference core. Meanwhile, sodium void reactivity in the C2 and C4 cores are smaller than in reference core, as shown in Table 3.32.

It is notable that further increasing minor actinide fission fraction in a critical fast reactor is very difficult. In the ‘two strata’ fuel cycle concept (i.e. the strategy of limited HLW transmutation cycle separated from commercial power generation cycle), ADSs may have the capability to achieve higher whole core minor actinide fission fractions.

3.3.3.5. Conclusions

This section presents the neutronic characteristics of two approaches to minor actinide nuclide transmutation in an SFR, including transuranic multi-recycling and transmutation in a dedicated burner reactor. The main conclusions are summarized as follows.

(a) Transuranic multi-recycling in a sodium cooled fast reactor core

Loading transuranics as the driver fuel will have little impact on the core kinetic parameters (β_{eff}, burnup reactivity swing and Doppler feedback), core neutron flux distribution or power density distribution. However, the sodium void worth will be increased to a small positive value, and the core breeding ratio is slightly reduced. Compared with the reference core, the most significant advantage of a transuranic fuelled core is that in-core minor actinides are consumed favorably with fuel burnup, which means minor actinides are transmuted. The consumption speed of transuranics in the transuranic fuelled core is around 18.8% faster than that in the reference core for the first transuranic cycle.

When transuranics are multi-recycled, for metal fuel their composition will achieve an equilibrium state and the final minor actinide equilibrium fraction in transuranics is about 3.8%. For the MOX fuel (reference core), the situation changes slightly: the minor actinide fraction first decreases to a minimum of 7.2% and then increases slowly upon accumulating curium. Meanwhile, the associated transuranic heat release and neutron emission rates are much lower in discharged metal fuel than those in the MOX fuel, especially when transuranics are recycled a sufficient number of times. The equilibrium fraction of fissile ^{239}Pu and ^{241}Pu in the plutonium for the MOX fuel and the metal fuel is 54% and 64%, respectively.

It can be concluded that this kind of closed fuel cycle strategy (i.e. loading integrated transuranics from the PWR used fuel as the driver fuel and multi-recycling it in the reference core) has significant advantages and is feasible from neutronics point of view. Firstly, proliferation resistance is enhanced while the high utilization of uranium resources in fast breeders is maintained. Secondly, the overall cumulated inventory of minor actinides in the nuclear power industry can be controlled effectively, as all the minor actinides are stored in the reactor core, without requirements for out-core storage. Grouped transuranic recycling in a fast reactor can make contributions to both breeding and transmutation, and is thus a prospective closed fuel cycle strategy to achieve the aim of sustainable development of nuclear energy.

(b) Dedicated sodium cooled fast reactor minor actinide burner

The design study was carried out for the minor actinide dedicated burner reactor core and two SFR burner cores with power levels of 1000 MW(th) and 1240 MW(th), respectively (C2 and C4 cores). The whole core minor actinide fission fraction reaches about 12% with the sodium void reactivity only about 4$, and the relatively high supporting ratio of minor actinide incineration of about 7.0 is achieved with minor actinide incineration rate of about 6.5% for one cycle in the burner core. These results indicate that complete incineration (fission) of the minor actinides generated can be achieved using only 12% of the minor actinide burner's capacity. It also should be noted that in the minor actinide burner reactor core, β_{eff} is about 320 pcm, which is about 85% of conventional fast reactor using plutonium as fuel, and the Doppler constant is approximately 240 pcm, which is much lower than that in a conventional fast reactor. In addition, the study shows that while increasing neutron leakage can effectively reduce reactor core sodium void reactivity, the minor actinide incineration rate will also be slightly decreased. For a minor actinide burner reactor in a two strata cycle strategy, when pursuing a greater supporting ratio of minor actinide incineration (e.g. >7.0 in this study), a higher minor actinide fission fraction is required, and then an ADS may be a more technically suitable option (see Annex XXVI on the CD-ROM accompanying this publication).

3.3.4. A French study on radioactive waste transmutation options

3.3.4.1. Introduction

This study was originally requested by the 2006 Waste Management French Act to obtain an assessment of industrial perspectives on partitioning and transmutation of long lived elements. These studies were carried out in collaboration with EDF, AREVA and the National Radioactive Waste Management Agency (ANDRA, Agence nationale pour la gestion des déchets radioactifs) and in a close link with Generation IV systems development. This legal requirement was detailed in the Decree of 2008 setting the requirements for the National Plan on Management of Radioactive Materials and Waste (PNGMDR), which calls for the CEA to coordinate research conducted on the separation–transmutation of long lived radioelements. This research is based on the analysis of technical and economic scenarios taking into account the possibilities of optimization between long lived HLW transmutation processes, their interim storage and their disposal in a geological repository.

In the SYNERGIES framework, the study belongs to Task 3, on the evaluation of options for minor actinide management, providing technical and economical assessment of different option for minor actinide transmutation in France. The complete case study can be found in Annex XXIII on the CD-ROM accompanying this publication.

3.3.4.2. Objective and problem formulation

The objective of the study is a technical and economic evaluation of fuel cycle scenarios along with different options for optimizing the processes between the minor actinide transmutation in fast neutron reactors, their interim storage and geological disposal of ultimate waste. Scenario evaluations take place in the French context which considers the deployment of the first SFR in 2040. By this date, the SFR technology should be mature. Several management options of minor actinides have been studied:

— Plutonium recycling in SFRs (minor actinides are sent to the waste);
— Plutonium recycling and minor actinide (or americium alone) transmutation in SFRs and in the homogeneous mode (minor actinides are mixed with reactor fuel);
— Plutonium recycling and minor actinide (or americium alone) transmutation in SFRs and in the heterogeneous mode (putting minor actinides in radial blankets on a depleted UO_2 matrix);
— Plutonium recycling in SFR and minor actinide transmutation in ADSs.

The key questions to be answered in the study are the following:

— What are the inventories and characteristics of the materials and waste produced by the various scenarios?
— What is the impact of the various scenarios on the features of the installations (reactors, fuel cycle plants and storage facilities) and the transport requirements?
— What is the impact of the various scenarios on geological disposal (geological disposal occupancy and safety, among other things)?
— What is the impact of each scenario on the radiological protection of the public and the workers?
— What is the economic impact of each scenario?
— What is the industrial risk inherent in each scenario?

3.3.4.3. Assumptions, methods, codes and input data used

The assumptions associated with the scenarios under consideration are based on industrial experience transposed as effectively as possible to these new material management options; they do not preclude any future process and technological developments. The scenarios analysed in this first phase have in common the consideration that the current series of reactors would be renewed at constant installed capacity (60 GW(e)) generating 430 TW(e)·h/year. 40 GW(e) of light water EPR type reactors would be deployed between 2020 and 2040, followed by 20 GW(e) of SFRs between 2040 and 2050. The date of 2040 corresponds to a general hypothesis of a possible start of deployment of these SFRs, which would also be consistent with the main renewal dates for power reactors and fuel cycle plants. The introduction of a second series of 40 GW(e) SFR would take place from 2080 to replace the EPR which have reached the end of their service life. Starting in 2100, nuclear power generation capability would consist entirely of fast reactors (see Fig. 3.127).

Among the scenarios considering the deployment of SFRs, several differentiated alternatives have been selected:

(i) Recycling of plutonium only (Scenario F4).
(ii) Recycling of plutonium and transmutation of all or part of the minor actinides in the homogeneous mode:
  — Of all minor actinides (Scenario F2A);
  — Of americium alone (Scenario F2B).

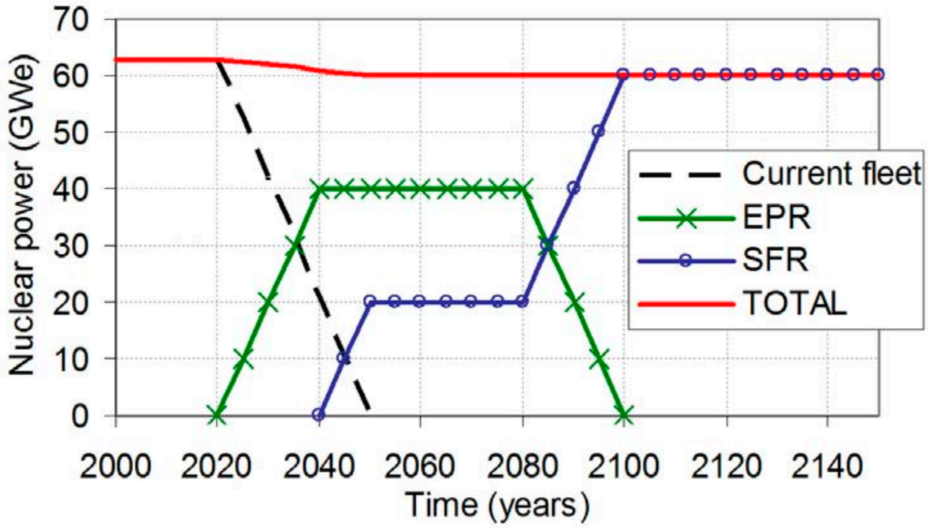


FIG. 3.127. Production by reactor technology.

(iii) Recycling of plutonium and of all or part of the minor actinides in the heterogeneous mode in the radial blankets:
- — Of all minor actinides (Scenario F1G);
- — Of americium alone (Scenario F1J);

(iv) Recycling of plutonium in SFRs and transmutation of minor actinides in a dedicated ADS stratum (Scenario F7).

The methods applied involved grouping under a number of key questions (all the questions of the various stake holders) and then, in a second phase, defining the indicators that serve to answer these questions. The questions are summarized in Annex XXIII on the CD-ROM accompanying this publication.

The results should be analysed through several criteria. Assessment criteria has to take into account the view of all the players (scientists, industry, politicians and public, among others), cannot be redundant and needs to form a coherent whole set that is as robust as possible. The following criteria were used to analyse different scenarios should consider technical and scientific aspects, requirements for potential industrialization and public acceptance:

- — Inventories and characterization of materials and waste;
- — Impact on the waste repository (footprint and safety impact on the industrial facilities, reactors, fabrication plant, reprocessing plant and interim storage) and transport needs;
- — The impact on radiological exposure of the public and workers;
- — Economic impact;
- — Industrial risks.

All of the scenarios described in this study refer, to varying degrees, to processes or technologies which have not been implemented at present, notably for industrial use and in some cases, which are still concepts. The maturity of the processes and technologies to be implemented in the different scenarios is a major parameter which is required for understanding the technical and economic risks related to the different options. Nevertheless, risks will be limited if the selected options provide sufficient flexibility and if the new technologies are implemented progressively. For instance, processes which are continuously updated through successive addition of new functions involve fewer risks than processes requiring dedicated facilities, which are, in most cases, not easily adaptable to new options.

It is obvious that these risks will be all the higher, as the technologies employed will not be mature. This is the case for the scenario involving the transmutation of minor actinides in ADSs. Although significant progress has been made regarding the feasibility demonstration, ADSs are complex systems, whose development requires the design of components with a high technicality and whose feasibility is not yet guaranteed.

For all of the scenarios described in this study, it is assumed that the fourth generation SFRs will be implemented from 2040. The feedback from fifteen years expected experience with the ASTRID prototype operation would contribute to the technological maturity for SFR and fuel multi-recycling. The SFR core concept considered was developed by the CEA and French partners [3.70, 3.71]. The ADS model selected is the one designed for the EUROTRANS project (ADS Pb–EFIT) [3.72].

3.3.4.4. Summary presentation and analysis of the results

(a) Inventory

Contrary to a system of water cooled reactors, which inevitably produces increasing amounts of plutonium (reaching 1600 t in 2150 for a 60 GW(e) PWR fleet fed with UOX fuel), a system of plutonium recycling SFRs would stabilize the plutonium inventory at about 900–1000 t. Stabilization implies that SFRs operate on a break-even core (i.e. that they produce as much plutonium as they consume).

The main results at equilibrium and interim period can be summarized. At equilibrium period, in the case of recycling plutonium alone in SFRs without minor actinide transmutation, the minor actinide content in the irradiated fuel is about 0.4% (compared to about 0.1% in a PWR UOX fuel). Transmutation of minor actinides requires considering, at equilibrium, a content of about 1.2% of minor actinides in the fuels in the case of transmutation in homogenous mode, in which all the SFRs are involved; or one row of radial blankets containing 20% of minor actinides in 75% of the reactors of the system; or the deployment of 18 ADSs of 385 MW(th) in case of transmutation in dedicated reactors (an ADS with a higher power could certainly lead to more attractive performances). Transmutation of americium alone requires at equilibrium in all SFRs, a content of about 0.8% in homogeneous mode or one row of radial blankets containing 10% of americium.

The interim period proves to be more restrictive, because the quantity of minor actinides to be transmuted and the number of fast reactors available are not necessarily matched. This is the case in particular between 2040 and 2080. This means: in homogenous mode, having to significantly exceed the limit of 2.5% of minor actinides in the fuel; and in heterogeneous mode, considering two rows of blankets containing 20% of actinides until around 2100. These results are conditioned by the assumptions made in the scenarios, and in particular the limitations associated with them. Hence, they demand further optimization of the interim phase to try to smooth the peaks encountered, which dimension the fuel cycle installations [3.73].

(i) Plutonium availability

If the deployment of the first wave of SFRs from 2040 raises no problem, it is important to anticipate the reprocessing of the spent fuels (cooling time reduced to 3.4 years instead of 5 years), or to alter the reactor concept in order to get the plutonium required to deploy the second wave of SFRs (using radial blanket for example). In these conditions, the deployment of a SFR reactor system as described in these scenarios appears feasible.

The deployment of ADS reactors is faced with a plutonium deficit of about 40 t. Relaxing the limitations applied to the scenario would probably help to circumvent this difficulty. Two alternatives can be examined: reducing the fuel cooling time and/or larger number of fertile assemblies.

(ii) Inventories of minor actinides

The transmutation of minor actinides helps considerably to limit the quantity present in waste, because with the exception of minimal losses, they are no longer automatically sent to waste. If the non-recycling of minor actinides means the continuous increase in their waste inventory (to reach nearly 400 t in 2150), the transmutation of all the minor actinides helps to stabilize this inventory at around 60 t, regardless of the transmutation mode selected (homogeneous, heterogeneous and ADS). Between these two extremes, the transmutation of americium implies a moderate increase in the waste inventory, due to curium and neptunium: the value reached in 2150 is about 150 t.

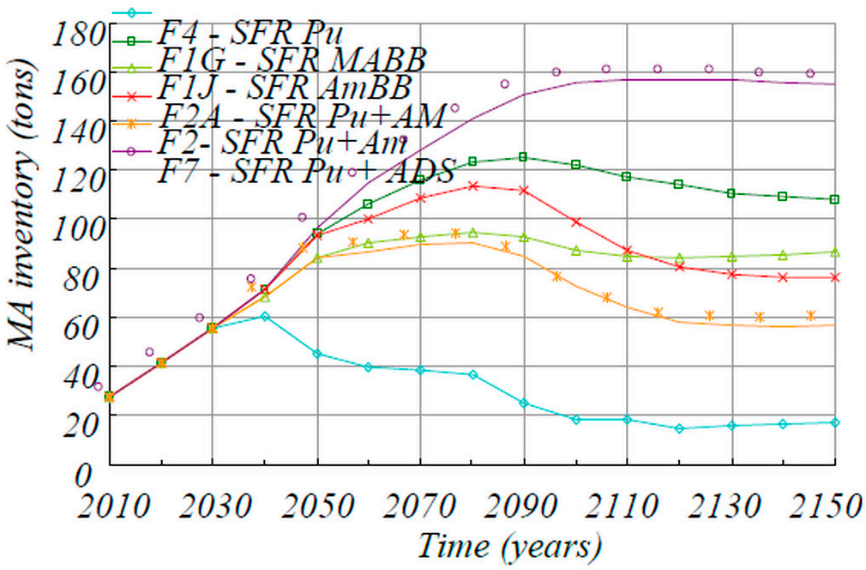


FIG. 3.128. Inventory of minor actinides in the fuel cycle.

(iii) Inventory in the cycle

The immediate consequence of implementing the minor actinide transmutation option is the increase of the minor actinide quantities in the cycle inventory, as shown in Fig. 3.128. It is worth to recall that the term ‘cycle’ here designates all the installations of the loop followed by the actinides (fuel fabrication plant, reactor, reprocessing plant and spent fuel storage). The not recycled part of minor actinide inventory is considered as waste and the sum up between recycled and waste forms the overall minor actinide inventory.

In the case of ADSs, the high level of inventory in the cycle is explained as follow: although the reactor inventory is comparable with the transmutation in SFR, the short duration of the irradiation cycle due to the low power of ADSs makes the inventory outside of the reactors (7 years: reprocessing + fabrication) proportionately larger. This term is dominant here.

(b) Impact on waste

ANDRA was asked by the CEA to assess the impact of the HLW and ILW generated by the various transmutation technologies on geological repository size. ANDRA considered the repositories similar in structure to those used in the Cigéo project ongoing for current nuclear power plants. The results allow comparing the underground footprint and the excavated volume for three scenarios (F4, F1G and F1J). The impact of the period of interim storage was also assessed. Approaches to optimize the footprint of the repository were put forward. The advantages and disadvantages of the various transmutation options are analysed in Refs [3.74, 3.75].

HLW and ILW–low level waste (LLW) are disposed of in separate underground zones. This arrangement offers independence in terms of: (i) the management of the various types of waste; and (ii) the phenomenological behaviour of each zone, in view of the specific characteristics of the waste contained.

The repository cells are constructed progressively with waste emplacement, according to a modular architecture which provides for a strict separation between mining and nuclear activities. The underground facility includes a common infrastructure built prior to the operational phase of the repository, a disposal zone for ILW and LLW and a disposal zone for HLW.

In Scenario F4, the first study phase concluded that an increase of the interim storage period from 70 to 120 years would provide a gain of 25% on the footprint of the HLW zone and 7% on the total excavated volume. The presence of americium in the waste restricts the densification of the repository because of a relatively low decay of the thermal power with time due to the long radioactive half-life of ^{241}Am. In the case of the transmutation of all minor actinides (Fig. 3.128), the increase of the interim storage period to 120 years allows a larger gain (60%) of the footprint of the HLW zone and 12% of the overall volume excavated.

Based on the results of the first study phase, the second study phase consisted of a search for ways of optimizing the design with the objective of a more drastic decrease of the repository footprint. This second phase has considered only an interim storage period of 120 years for HLW. Indeed, this assumption associated with transmutation scenarios provides a significantly higher gain than a 70 year interim storage period. Compared to the multi-recycling of plutonium in an SFR, the transmutation of minor actinides associated with a design optimization of the repository would provide the following:

— A reduction by a factor of up to 7.3 (americium) to 9.8 (minor actinides) of the footprint of the HLW disposal zone after an interim storage period of 120 years;
— A total reduction by a factor of 3 of the repository footprint taking into account ILW–LLW and common infrastructures;
— A total reduction by a factor of 2 of the excavated rock volume.

Along with a reduction of the footprint of the HLW disposal zone, the partitioning and transmutation of actinides also decreased the thermal phase duration. After an interim storage period of 120 years, the thermal phase is reduced to about 200 years, compared with 1000 years without transmutation.

The long term radiological impact of the deep geological repository is not reduced by partitioning and transmutation of actinides. Indeed, this impact is dominated by long lived fission and activation products with a higher mobility in the geosphere (^{129}I and ^{36}Cl).

In the normal long term evolution safety scenario, the study shows that the densification of the repository as allowed by partitioning and transmutation does not significantly change the radiological impact of fission and activation products, despite concentrations in the near field increase with densification.

In an altered evolution scenario such as one involving intrusive drilling, the impact of fission and activation products may increase to some extent because of the densification of the repository. Nevertheless, this impact remains acceptable with regard to the dose limit (0.25 mSv/a) provided by the basic safety guide issued by the French Nuclear Safety Authority (ASN, Autorité de sûreté nucléaire).

(c) Impact on the cycle facilities

(i) Impact on manufacturing

Powder metallurgy processes comparable to that employed in the MELOX plant can be considered for the fuel manufacturing. Such processes include successive steps involving powder preparation, the manufacture of pellets via lamination and sintering, the manufacture of rods and the installation of the subassemblies. Nevertheless, the presence of minor actinides requires reinforced shielding systems (neutron emission and gamma radiation). Furthermore, the heat released by the radioactive materials involves making specific provisions for controlling temperatures during the manufacture of minor actinide bearing subassemblies. However, as americium and the mixture of minor actinides are less penalizing than plutonium, controlling the criticality risk, which is possible by means of the customary control procedures, is not problematical. Table 3.33 compares the thermal power and neutron emissions of the oxide powders used for manufacturing the fuels. These values are standardized with respect to the SFR fuel without minor actinides.

It is clear that the scenarios involving the transmutation of all minor actinides are extremely impeded by the presence of curium, and particularly of the ^{244}Cm isotope. The manufacture of the fuels would obviously require the construction of a shielded enclosure with remote controlled devices. With high curium content, whole new technology development will be required (more pronounced for the ADS option). The scenarios with transmutation of americium are less restrictive for manufacturing operations [3.76].

(ii) Impact on the processing

Minor actinide bearing subassemblies are processed in facilities designed to receive the different types of spent fuel to be recycled (UOX, MOX and SFR). Processing operations are assumed to be based on the hydrometallurgy processes, such as at La Hague, including for ADS fuel. ADS fuel can also be processed by pyrometallurgy. The processing facility is broken down into workshops. Most of the workshops are dedicated to separate the nuclear

TABLE 3.33. THERMAL POWER AND NEUTRON EMISSION OF POWDERS DURING MANUFACTURING (AT EQUILIBRIUM)

	MA transmutation				Am transmutation	
Scenario	F4	F2A	F1G	F7	F2B	F1J
Fuel	Fr–core	Fr–core	MABB	ADS	Fr–core	AmBB
Thermal power (W/kg)	1.5	9	55	160	3	7
Neutron emission (relative value)	(1)	(120)	(1600)	(3500)	(1.4)	(3)

Note: ADS — accelerator driven system; BB — bearing blankets; Fr — fast reactor; MA — minor actinide.

material from metal structures and to place it into solution, to separate via extraction cycles with solvents the chosen elements, to convert the separated elements into oxides and to condition structural waste and fission products.

The scenarios including the transmutation of minor actinides obviously involve the implementation of a process for separating chosen elements. According to the scenarios, this process may consist in a sequential separation process (DIAMEX-SANEX), in which the actinides are recovered separately, in a combined separation process (GANEX), in which plutonium and minor actinides are extracted together, or in an individual separation process (EXAM), in which americium can be recovered selectively. All of these processes are still being developed. Their feasibility has been demonstrated at the laboratory scale; however, their industrial implementation still requires a long R&D process.

Studies on reprocessing facilities for core fuels recycling (minor actinides or americium) or bearing blankets recycling (minor actinides or americium) do not show important difficulties. However, scientific and technical feasibility has to be investigated for ADS spent fuels.

Criticality constraints have been analyses in preliminary studies: additional analyses are required for specific functions as conversion of product containing curium. Thermal and radiation constraints have also been considered: the controlling systems and biological shielding are to be reinforced, particularly during the minor actinide conversion step [3.76].

(iii) Impact on transport

The heat released by new or spent actinide bearing subassemblies can be a problem for transport operations between the reactors and the fuel cycle plants (see Table 3.34). Impacts of transmutation scenarios on fresh and spent fuels annual transport have been evaluated. Thermal, radiation and criticality constraints have been taken into account to propose cask concepts for normal conditions. No difficulties appear for americium transmutation scenarios (homogeneous or heterogeneous). When fuels contain curium, transport uncertainties increase because of important heat release requiring dividing fresh fuels and technological innovations development (MABB and ADS).

The number of canister to be transported and the number of transport journeys required are significant factors for assessing the scenarios (see Fig. 3.129) [3.76].

(d) Impact on the reactor

(i) Impact on the core

The homogeneous transmutation process will degrade the safety coefficients of the core more or less significantly according to the minor actinide content being considered. A limit of 2.5% is generally accepted for a large SFR core [3.71]. In the case of the heterogeneous transmutation (MABB and AmBB), the minor actinides to be transmuted are introduced on the periphery of the core and, even with a high content, their impact on the reactivity coefficients remains marginal.

TABLE 3.34. THERMAL POWER OF NEW AND SPENT SUBASSEMBLIES (EQUILIBRIUM WILL BE REACHED AROUND 2130)

	MA transmutation				Am transmutation	
Scenario	F4	F2A	F1G	F7	F2B	F1J
Fuel	Fr–core	Fr–core	MABB	ADS	Fr–core	AmBB
New (kW/ assembly)	0.3	1.3	9	7	0.6	1.3
Spent (5 y, kW/ assembly)	1.3	2.2	11	7	1.8	(3)

Note: ADS — accelerator driven system; BB — bearing blankets; Fr — fast reactor; MA — minor actinide.

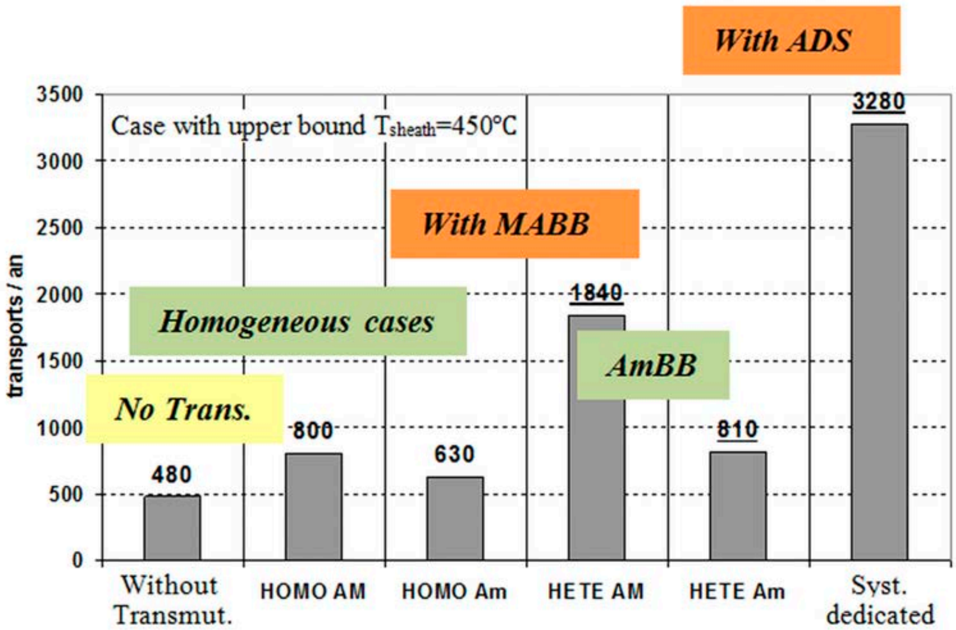


FIG. 3.129. Annual transport operations of fresh and used fuels.

(ii) Impact on the handling of fuel

Some specific biological shielding or cooling system will probably be necessary for handling subassemblies containing minor actinides and particularly for MABB. The handling of spent subassemblies is greatly conditioned by their residual power. At present, there are two limits: for unloading subassemblies out of the reactor vessel, the maximum acceptable power amounts to 7.5 kW if the environment is gaseous (possible solution for the EFSR) or 20 kW if the operation is performed in the liquid sodium coolant (as in case of a transfer bucket such as on Phénix or Superphénix). Research studies have been conducted on the possibility of increasing this last value to 40 kW. Concerning the underwater storage of the subassemblies, it will be necessary to clean them beforehand in order to remove all traces of sodium. At present, the maximum power for cleaning is of 2.5 kW. Research work is being performed to reach 7.5 kW.

There is also the impact of the implementation of MABB. Even when considering a transfer in sodium, the AmBB with 20% americium could not be unloaded out of the reactor vessel before approximately fifty days. Therefore, providing a storage area inside the vessels appears to be a compulsory requirement.

Cleaning the MABB and AmBB with 20% of minor actinides or americium could not be envisaged before at least 15 and 7 years, respectively and probably later since the uncertainty on the residual power has to be taken into account. This means that an intermediate storage area (outside of the reactor vessel) in sodium is necessary and it needs to be sized accordingly. The optimization of the AmBB concept allows reducing these drawbacks (AmBB, 5 cycles instead of 10 cycles with 10% of americium). In this case, there is no technical impact on the reactor vessel of the reactor.

(iii) Impact on the external storage

The external storage is a buffer used to store the new assemblies temporarily before loading and to store the spent assemblies while waiting for their decay heat to become compatible with the washing device. The size of the external storage depends on precise knowledge of the decay heat of the spent fuel assemblies and on the allowable power of the washing device. To account for these different uncertainties, two wrapper values for the power of the washing device are selected: 7.5 kW and 4 kW. With this hypothesis and with the value of the decay heat (see Fig. 3.130), the size of the external storage and the cooling delay can be defined for the type of assembly. The results are given in Table 3.35.

The assessment of the size of the external storage shows the impact of the couple decay heat and washing device, especially in the case of a low, allowable power of the washing device. In the worst case, it was necessary to wait for 60 years before washing, which reveals the very long lifetime of the external storage: about 120 years, 60 years for reactor lifetime plus 60 years for the cooling of the latest fuel assemblies [3.77].

(iv) Impact on reactor availability

The introduction of minor actinides leads to an increase in the number of actions during the refuelling operation, such as reshuffling or increasing movement of the minor actinide assemblies. Therefore, the availability is slightly reduced. An assessment of the handling time with the CEA tool OCTET leads to an increase in this time of one equivalent day at every reloading operation. As the opening and closing time is 400 days, the availability is reduced by 0.25% [3.77].

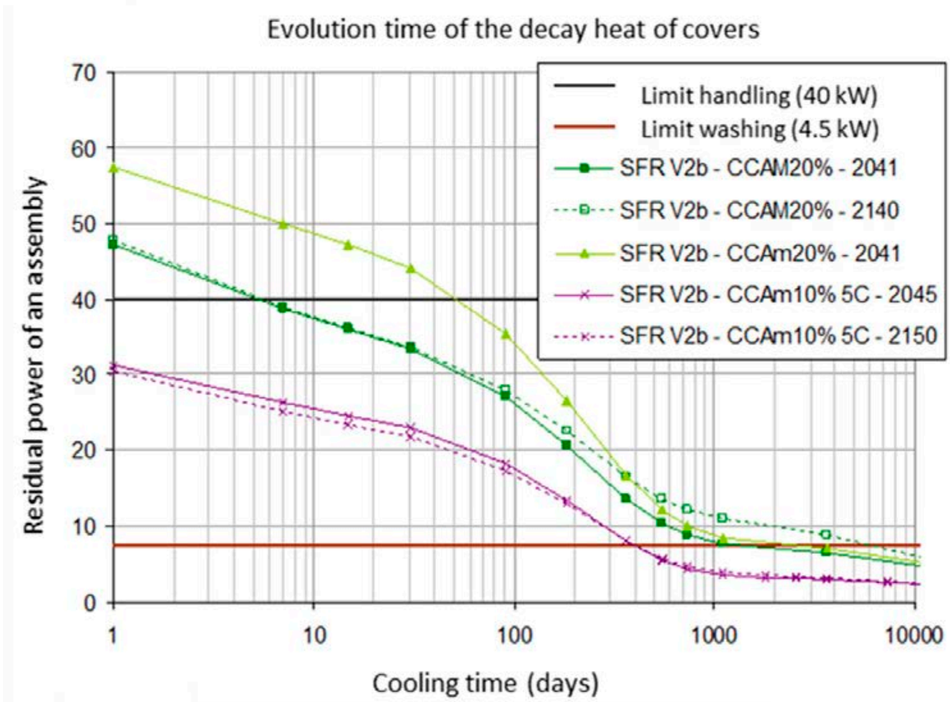


FIG. 3.130. Residual power of spent subassemblies.

TABLE 3.35. MAIN FEATURES OF THE EXTERNAL STORAGE

Permissible power by the washing device	7.5 kW		4 kW	
	Years	No. of positions	Years	No. of positions
Only Pu fuel	0.5	242	1.2	362
AmBB 20%	7	310	60	928
MABB 20%	15	382	60	928
AmBB 10%	1.1	248	3	572
Homogeneous MA/Am (at equilibrium)	0.6	242	1.5	543

Note: BB — bearing blankets; MA — minor actinide.

(e) Economics

The purpose of these studies is not to bring up issues about the economics of the nuclear industry in France and in the world. Therefore, providing power production costs in absolute terms is not meaningful, as these depend on the particular industrial and marketing environments in which the plants will be constructed. Moreover, several fuel cycle related processes will need new technology development and subsequent industrial assessment, which increases cost evaluation uncertainties. Comparing production costs in relative terms is quite sufficient for the exercise conducted in this study, which consists in a simple intercomparison analysis of the different scenarios.

The comparison of the levelized cost of electricity (LCOE) per MW·h for each scenario is conducted when the equilibrium is reached (when a total SFR fleet is deployed). For the computation of cycle costs in the LCOE per MW·h, each fuel step was taken into account (front end and back end). For each step, the unitary cost was evaluated and, for discounting purposes, the mean time interval with regard to the fuel irradiation time.

Two sets of discount rates have been chosen enabling to assess the sensitivity of the results to this parameter. The first case is representative of a ‘private estate’ economic approach. The discounting is performed with a rate of 8% over the first 30 years and then 3% after that [3.74]. The second case corresponds to a ‘public’ or ‘public interest’ economic approach. The discounting is performed with a rate of 4% over 30 years, which then decreases to 2%.

In the first approach (Approach A), economic calculations were carried out with a unit cost database for reactors and cycle operations. In this database, the operating costs are assessed by analogy with existing facilities while assuming advanced cost saving developments. The second approach (Approach B) does not account for the advanced developments considered in Approach A owing to the fact that they might not provide suitable industrial solutions (i.e. due to modified regulations). Furthermore, Approach B is based on hypotheses, which are much more cautious regarding certain major parameters (which are not clearly understood) such as, for example, the plant availability factor (Kd).

(i) Results with Approach A

Table 3.36 presents the average production costs for two scenarios. An index of 100 has been allocated to the average production costs for 2120–2150 (representative of the fleet at equilibrium) of scenario F4 (without any transmutation). The index 100 does not represent the same value for the two sets of discount rates.

With the hypotheses which have been selected, approach A shows that the cost overrun related to the transmutation in SFR would amount to around 4–9% overall. As for the cycle alone, cost overruns could reach 50–60%. However, the cost overrun for the reactor item would not exceed 2%. There would be no large distinction from an economic viewpoint between the homogeneous and heterogeneous transmutation options; only the transmutation in ADSs could generate a significant cost overrun of around 26%.

It is also observed that the relative order of merit of the scenarios is only slightly affected by the choice of the discount rate due to the fact that the cash flow chronologies are very similar for the different scenarios. A sensitive

TABLE 3.36. STANDARDIZED PRODUCTION COSTS

	Total	Reactor	Cycle
Scenario a: discounting rate 3–8%			
Without minor actinides	100	94	6
Heterogeneous all minor actinides	106	96	10
Heterogeneous only Am (20%, F1J)	104	95	9
Heterogeneous only Am (10%, F29)	105	95	10
Homogeneous all minor actinides	108	95	12
Homogeneous Am	105	95	10
In accelerator driven system	126	116	10
Scenario b: discounting rate 2–4%			
Without MA	100	91	9
Heterogeneous all minor actinides	107	92	14
Heterogeneous only Am (20%, F1J)	105	92	13
Heterogeneous only Am (10%, F29)	107	92	15
Homogeneous all minor actinides	109	92	17
Homogeneous Am	106	92	13
In accelerator driven system	124	110	14

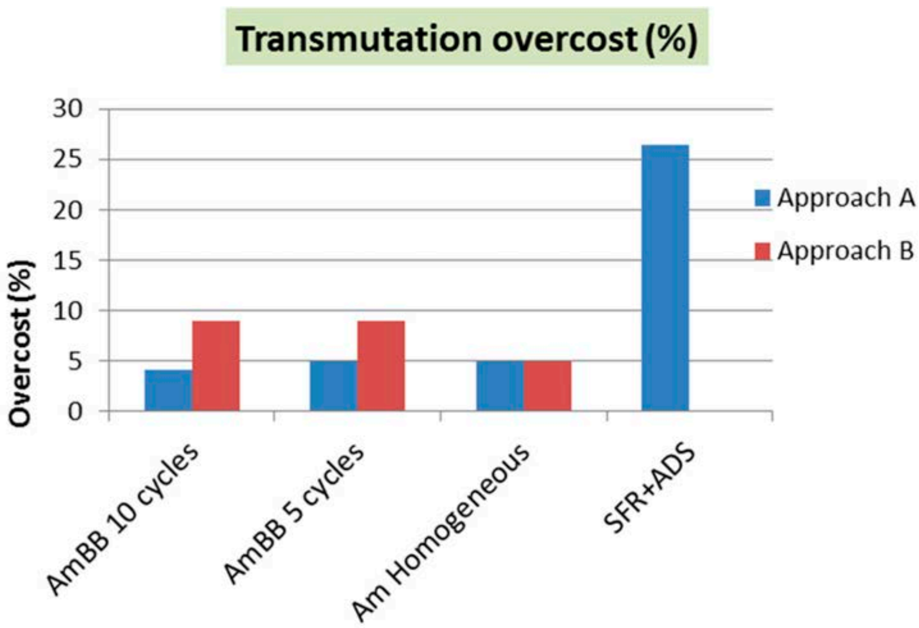


FIG. 3.131. Transmutation overcost between Approaches A and B.

study indicates that the most important items are SFR investment and operating costs, and then to a lesser degree, fuel processing and manufacturing costs. The same conclusions apply to the 2–4% discounting rate.

(ii) Results with Approach B

The economic calculations were modified and more penalizing values were used, particularly concerning the items which had been identified as important in the sensitivity analysis. Different values were chosen compared to Approach A for three reasons: (i) there are technical divergences leading to different cost assessments; (ii) there are different philosophies, particularly concerning future requirements regarding safety and radiation protection, and it is assumed that the technological developments will not be able to deal with such matters; and (iii) there is a greater caution concerning certain aspects which are not clearly understood at this stage (e.g. Kd).

The cost overrun related to the transmutation in SFR would amount to around 4–9% overall and around 26% in the case of ADSs (see Fig. 3.131). So, except ADSs, the economy is not very discriminating on the choice of the transmutation option.

3.3.4.5. Conclusions

These studies have obtained many important results on a set of defined scenarios and with an improved and satisfactory methodology related to the advantages and drawbacks of minor actinide transmutation options and consequences on fuel cycle plants. Only the transmutation of all minor actinides, through multi-recycling operations in SFRs, enables year stabilization of their inventory over time. The transmutation of minor actinides significantly reduces their inventory in the geological repository due to the fact that they are no longer transferred to the waste packages. The amount of minor actinides present in the waste is essentially determined by the quantity which is already present when the transmutation is implemented.

The immediate consequence of the reduction of the minor actinide content in the waste is an increase of the minor actinide inventory in the cycle (reactors and fuel cycle plants). As transmutation is a relatively slow process, the minor actinides accumulate in the facilities prior to reaching an equilibrium level. The calculated inventories vary from 60 t to 160 t according to the transmutation concepts. It is recalled that, at the same time, the plutonium inventory amounts to around 1000 t.

Reducing the thermal load of HLW packages due to the transmutation of americium greatly reduces the underground area covered and the excavated volume of the HLW disposal modules without questioning the performances and safety of the repository. The transmutation of americium and minor actinides would result in a reduction by a factor up to 7.3 (americium) to 9.8 (minor actinides) of the footprint of the HLW disposal zone after an interim storage period of 120 years, a total reduction by a factor 3 of the repository footprint taking into account ILW and LLW and common infrastructures.

As can be expected, calculations reveal high contents of minor actinides at the fuel manufacturing and processing steps, which will generate significant design modifications for dealing with obvious thermal and radiation protection problems. The complexity of the operations carried out during the operating phase (loading/unloading, interim waste storage, and transport) will also be increased. Scenarios involving the transmutation of all minor actinides are extremely impeded by the presence of curium and the implementation constraints often exceed that of the scenarios, in which only americium is transmuted, by one order of magnitude.

Economic studies have been conducted on the different scenarios to determine the impact of the transmutation of the cost of electricity production. They show that the cost overrun related to the transmutation process could vary between 5% and 9% in SFRs and 26% in the case of ADSs according to the assumptions being considered. The transmutation of curium raises design constraint issues for all facilities whereas its impact on reduction of HLW zone is low compared to the impact of americium transmutation.

3.3.5. Comparative economic analysis of selected synergistic and non-synergistic GAINS scenarios

3.3.5.1. Introduction

Nuclear systems are complex, implying long term capital intensive programmes, with construction costs for large reactor units in the range of US $2–10 billion and substantial investments needed for fuel cycle facilities [3.4, 3.41]. The implementation of nuclear programmes can be a significant economic challenge for NG3 newcomer countries and countries with a small nuclear programme. The total investment required to install an NES should be compatible with the ability of potential investors (either governmental or private) to raise the necessary capital at the time of committing to construction of nuclear power plants and other nuclear facilities [3.78].

Installing new fuel cycle capacities requires additional significant capital investments. Investments for a uranium enrichment facility were estimated to be about US $2–4 billion in 2008 [3.79]. Conversion and UOX fuel fabrication plants are not as capital intensive, but they could raise the issue of economy of scale at the country level. Investments in back end facilities are the most challenging. The Organisation for Economic Co-operation and Development [3.4] estimates overnight investments in an interim storage facility (capacity 8000 t HM) to be US $1–1.5 billion in 2010. The overnight investment costs of the integrated facility in France that includes La Hague reprocessing plant and MELOX MOX fuel fabrication plant was estimated to be about US $20 billion in 2010 [3.4, 3.80]. The capital cost of THORP, in the United Kingdom, with 1200 t HM/year nominal capacity, was estimated to be about US $5.32 billion in 2010, and capital cost of the Mixed Oxide Fuel Fabrication Facility was estimated to be US $7.7 billion in 2010 [3.4]. Geological repository investment cost varies in the range of US $5–10 billion in 2010 depending on facility capacity in the range of 20 000–60 000 t HM [3.4]. The data on the Yucca Mountain deep geological repository (120 000 t HM) were about US $35 billion in 2010.

Some countries and nuclear companies may be able to meet the investment challenge of NES development and deployment, but are less likely to have the financial strength to finance nuclear power construction and an associated nuclear fuel cycle. International cooperation and international markets can alleviate this problem as international fuel cycle facilities can produce nuclear fuel cycle services for several countries, as is the case today for most front end services.

The present study is part of Task 1, on the evaluation of synergistic collaborative scenarios of fuel cycle infrastructure development. Task 1 aims to provide a framework of scenarios for NESs based on best estimates though illustrative regional NES scenarios with and without collaborative agreements are addressing fuel cycle options and synergies. Following SYNERGIES, the present study examines drivers and impediments on a collaborative path to sustainable NESs with a specific focus on economics. The complete case study can be found in Annex XVII on the CD-ROM accompanying this publication.

3.3.5.2. Objective and problem formulation

The SYNERGIES project considers economics as an important component in assessment of benefits and disadvantages of the various collaborative architectures. The objective of the study is to show the difference between synergistic and separate (non-synergistic) cases using the key indicators for nuclear fuel cycle investment cost and LUEC. Nuclear fuel cycle investment is an important component in assessing the advantages and disadvantages of the various collaborative architectures; low fuel cycle cost is one of the advantages of nuclear power, and maintaining low fuel cycle cost is an important factor to economic viability. The study is based on the scenario approach developed in the GAINS project [3.52]. The heterogeneous model for the NG1, NG2 and NG3 groups is the basis for assessment of advantages and disadvantages of cooperation between groups (synergistic) and separate group development (non-synergistic) cases.

The study also explores how cooperation between technology holder (NG1) and technology user (NG3) countries impacts the structure of electric energy generation growth in technology holder group of countries (NG1) and how change in the NG1 electric energy production structure will lead to the changes in the entire nuclear fuel cycle structure. The study examines how countries could benefit in the short term from cooperating on long term storage facilities. The accumulation of UOX spent fuel in long term storage of NG3 will steadily increase, achieving significant amounts by the end of century in non-synergistic case. An investment in spent nuclear fuel storage in NG3 can have a notable contribution to the total fuel cycle. Cooperation between NG1 and NG3 can resolve the issue of spent fuel accumulation in both regions.

3.3.5.3. Assumptions, methods, codes and input data used

The study is based on scenario approach developed in the GAINS project [3.52] to model and examine more specifically the various forms of collaboration among the suppliers and users, and to identify those which ensure a mutually beneficial approach to sustainable NESs. The study assumes global electricity generation to be 1500 GW·year in 2050, 5000 GW·year in 2100 and then flat growth until the end of modelling period. The heterogeneous model for the NG1, NG2 and NG3 groups is the basis for assessment of advantages and disadvantages of the cooperation between groups (synergistic) and separate group development (non-synergistic). The NG1 and NG2 share is maintained as a nominal fraction of 40% and 20% in 2100 (see Fig. 3.132). A detailed description of the assumptions behind GAINS is provided in Appendix III.

Two cases were analysed: non-synergistic and synergistic. In the synergistic case there is shipment of nuclear material between groups whereas there is not any nuclear material movement between groups in non-synergistic case. Natural uranium is equally accessible for all groups in both cases. In the non-synergistic case, limitation on LWR reprocessing capacity was imposed up to rate 850 t/year until 2050 and additionally up to 3000 t/year after 2050. In the synergistic case, the constraint on the reprocessing capacity was increased up to 3000 t/year of spent fuel after 2030, in association with the introduction of an international centre.

The comparison of cases is based on a simplified approach that assumed only use of nth-of-a-kind (NOAK) for fuel cycle facilities, an acknowledgement that it is not mutually beneficial at NOAK then it is also unlikely to be mutually beneficial at first-of-a-kind (FOAK).

Calculations for investment in nuclear fuel cycle facilities for non-synergistic and synergistic cases were performed with the MESSAGE tool, using methods described in Appendix II. The investments in a particular nuclear fuel cycle facility are calculated as sum of capital investment uniformly distributed over constriction time (5 years for all facilities). Lifetimes are assumed to be practically unlimited except for reprocessing facilities, which are assumed to have a 60 year lifetime. The load factor of nuclear fuel cycle facilities is assumed to be 1. Total investments in fuel cycle scheme are the sum of investments corresponding to each stage of the nuclear fuel cycle.

The objective is not to give an accurate cost calculation, but to observe the relative difference between two cases. Investments in the nuclear fuel cycle are based on reference costs (see Appendix II). Investments are calculated first for the separate (non-synergistic) nominal case in NG1 and NG3 groups, and then for the synergistic nominal case in NG1 which provided nuclear fuel cycle services for NG3 based on reference costs (R approach). Reference fuel cycle facilities correspond to reference size facilities for moderate national nuclear power programme and reference costs (see Appendix II). For small nuclear power programme with a few GW(e) nuclear facilities can be scaled to national size and cost based on economies of scale (N approach). Then, cooperation among groups in terms of economy of scale is explored for synergistic case. The most expensive fuel cycle facilities including reprocessing and recycling are scaled to international center size and cost (I approach).

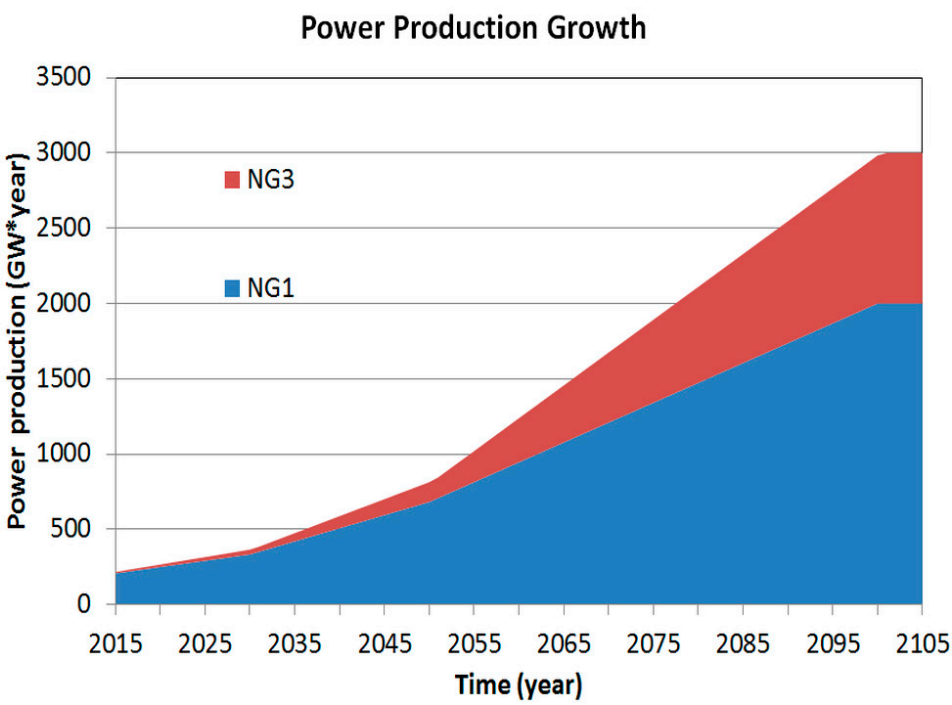


FIG. 3.132. Per annum electric energy generation growth, NG1 and NG3.

Electricity generation cost method is based on the LUEC model described in Appendix II. This model is very useful for economic comparison of different types of power plant in a general frame, particularly with a small amount of additional detailed information like bond emissions, equities and other financing tools. In this study, LUEC costs for LWRs and fast reactors are calculated with a focus on fuel cycle component. The NEST tool — an Excel and Visual Basic for Applications based spreadsheet developed by the INPRO group as the part of the NESA support package — was used to calculate all parameters of economics envisaged in the INPRO methodology (including LUEC and NPV, among others). NEST includes an example of LUEC calculation for different nuclear reactors with different fuel cycles (i.e. once through and closed fuel cycles).

A set of economic and technical input data is needed to estimate economic indicators. The necessary input data for fuel cycle and reactor for NES to be analysed in SYNERGIES collaborative project were collected. Each facility of the nuclear fuel cycle is represented with its technical and economic data (i.e. capital costs, capacities, load factors and lifetimes). The objective of the study is mainly to show the relative impact of different factors to the NES architectures, particularly the relative difference between synergistic and separate (non-synergistic) cases. The intention is not to perform an accurate cost calculation, the data used might not reflect the actual industrial value. For the comparative economic analysis, it is important to use a consistent set on economic data with the proper proportion of fuel costs rather than absolute values. If these costs increase or decrease proportionally, the percentage difference in costs will be the same. The economic data on reactors and fuel cycles were drawn from published literature, although data are subject to change in the future and should be updated when new information is available. The data collected are suitable for evaluating the economic impact of advances in technologies (introduction fast reactor and closed fuel cycle), changing economies of scale, cooperation among suppliers and users of fuel cycle services, and changing uranium costs.

3.3.5.4. Summary presentation and analysis of the results

Cooperation between NG1 and NG3 impacts the structure of electric energy generation growth in NG1, since more material would be available for fast reactors in NG1. Figure 3.133 compares the electric energy production from fast reactors in NG1 for separate and synergistic cases. The percentage of fast reactor commissioning increases by an average of 30% in the medium term (2030–2050). In the long term, first it is maintained at the same level (2050–2065) and then increases by 40% (2065–2100) in comparison with the separate case. The difference in the medium term occurs mainly due to LWR spent fuel scale reprocessing (3000 kt U/year versus 850 kt U/year); in the long term, it increases mainly because more LWR fuel from NG3 is available for reprocessing in NG1 (see Fig. 3.134). The change in the structure of NG1 electric energy production leads to the change in fuel cycle structure, from mining to reprocessing. Investments also change even under the same reference cost for separate and synergistic cases.

Figure 3.135 summarizes investments to all fuel cycle stages including mining, milling, conversion, enrichment, UOX fuel fabrication, MOX fuel fabrication, UOX reprocessing, MOX reprocessing and long term spent fuel storage facilities for NG1 in the separate case. Investment in the fuel cycle is represented as relative values in dimensionless form (see Appendix II). Investment in LWR spent fuel reprocessing is the major contributor to the total nuclear fuel cycle investments in 2025–2045; this can be a serious barrier to innovative NESs in the medium term.

Figure 3.136 shows total investments in all fuel cycle stages in the NG3 fuel cycle for the separate case. The result was obtained using the same approach as for NG1. Investment structure differs from those of NG1. Investment in enrichment facilities is the major contributor to the NG3 fuel cycle. Moreover, construction of long term spent fuel storage in NG3 requires a significant investment after 2050 while spent fuel storage in NG1 fully depletes around 2075.

Figure 3.137 summarizes investments in all fuel cycle stages (mining, milling, conversion, enrichment, UOX fuel fabrication, MOX fuel fabrication, UOX reprocessing, MOX reprocessing and long term spent fuel storage facilities) in the NG1 fuel cycle for the synergistic case. The results are obtained using the reference cost approach (R) as in the separate case. Investments in LWR spent fuel reprocessing remain the major contributor to the total investments in fuel cycle. A comparison of annual investments in the fuel cycle is shown in Figs 3.137 and 3.138 for reference separate and synergistic cases.

Figure 3.139 provides a comparison of investments in fuel cycles for the separate and synergistic cases in relative form, with values for the synergistic case divided by values for the separate case. Differences in the figures

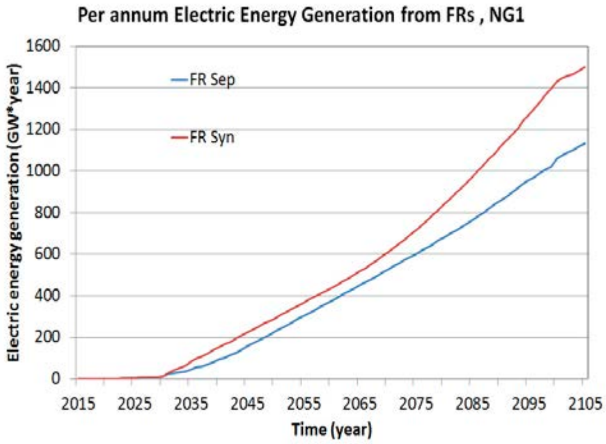


FIG. 3.133. Fast reactor per annum electric energy generation growth in NG1.

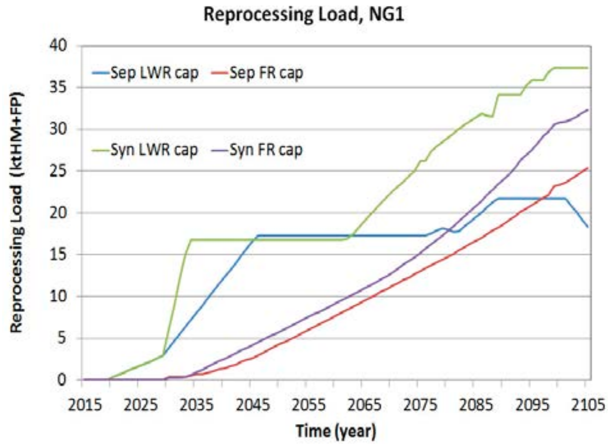


FIG. 3.134. Reprocessing load.

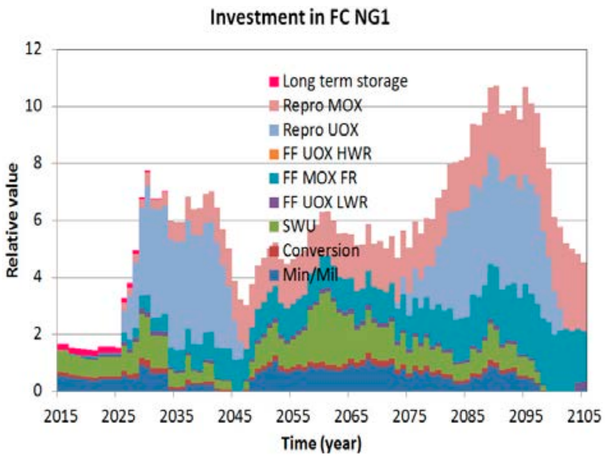


FIG. 3.135. Nuclear fuel cycle investments in NG1 (separate case, reference cost).

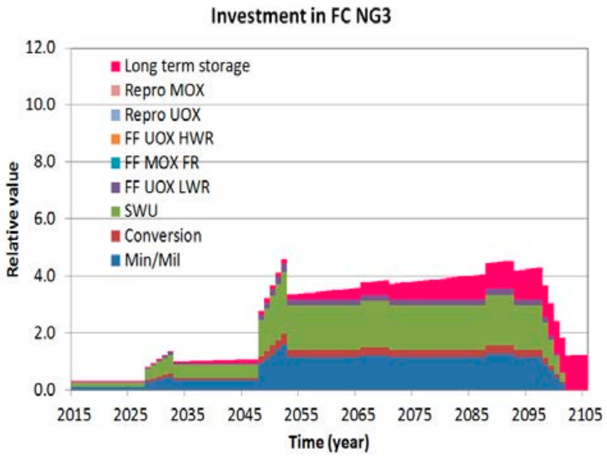


FIG. 3.136. Nuclear fuel cycle investments in NG3 (separate case, reference cost).

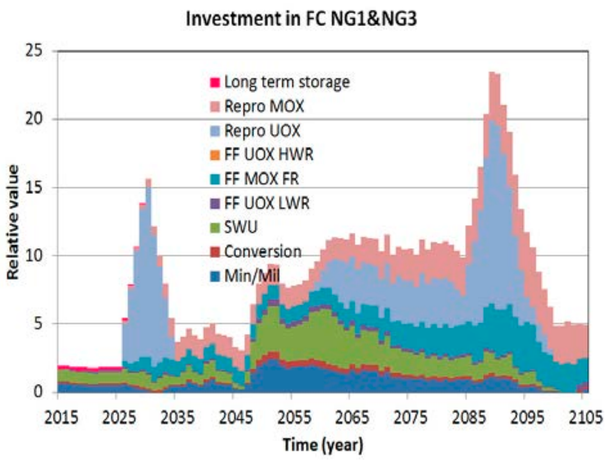


FIG. 3.137. Nuclear fuel cycle investments for the synergistic (R) case.

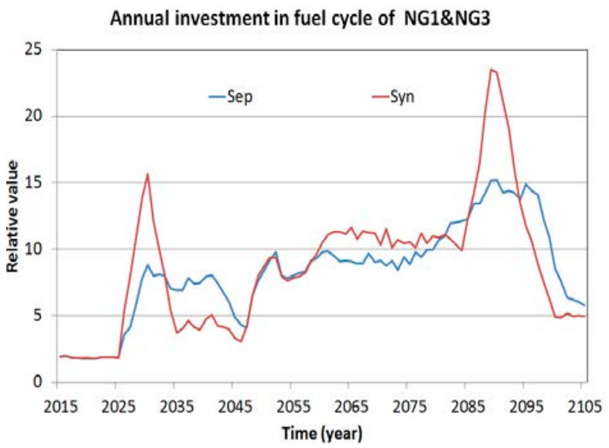


FIG. 3.138. Nuclear fuel cycle investments for the separate (R) versus synergistic (R) case.

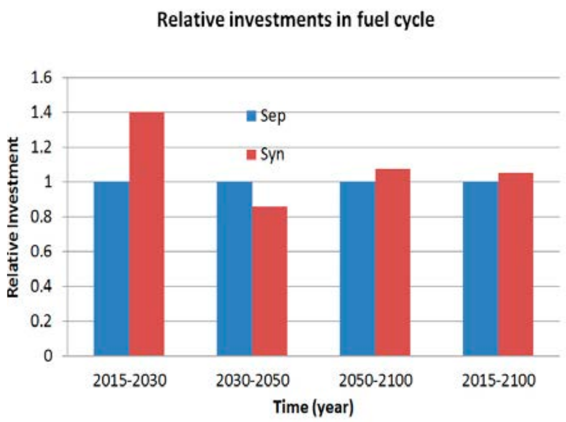


FIG. 3.139. *Relative investments in fuel cycle for separate (R) versus synergistic (R) cases.*

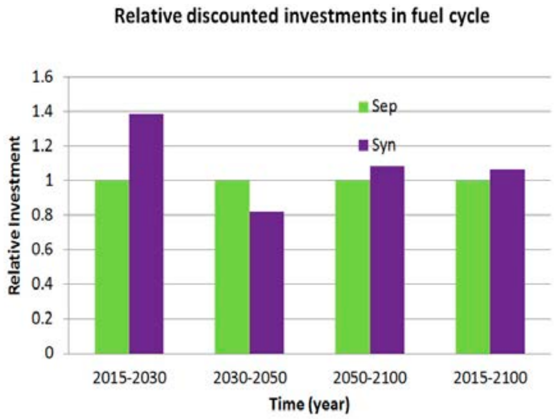


FIG. 3.140. *Relative discounted investments in fuel cycle for separate (R) versus synergistic (R) cases.*

are due to assumptions about the scale of LWR spent fuel reprocessing and movement of fresh and spent fuel among regions. Both cases are assumed to have the same reference costs. Under these conditions the main issue related to the high investment in LWR reprocessing facilities in the period 2025–2035 for the synergistic case. Therefore, investment in the synergistic case is 47% higher than for the separate case in the short term, the period 2015–2030. In 2030–2050, the synergistic case investments are 21% less than investments for the separate case due to ongoing commissioning of LWR spent fuel reprocessing facilities in the separate case. Total investments during 2050–2100 are 7% higher than for the separate case. Investments for the whole modelling period (2015–2100) become comparable for both cases, with 4% higher for the synergistic case.

Accounting for a discount does not change the conclusion qualitatively. Figure 3.140 gives the discounted annual and total investment cost for a discount rate of 5%. Discounting is more sensitive to the near term rather than more distant term investments. It evens differences between the separate and synergistic cases in the short (2030) and medium term (2050), and there is a slight impact in the long term (2100).

Since the investment in reprocessing and recycling facilities is one of the most important issues, the impact of economies of scale on fuel cycle investments for the separate and synergistic cases are taken into consideration. A national cost approach to the separate case and a reference cost approach for the synergistic case is applied. The result is given in Figs 3.141 and 3.142. Scaling to the national facility sizes and corresponding costs for the separate case leads to increasing fuel cycle investments. In 2030–2050, the separate case investments are still more than investments for the synergistic case, but the difference between cases is 20%. In 2030–2050, the synergistic case investments are 47% less than investments for the separate case. Total investments during whole modelling period (2015–2100) become 24% less for the synergistic case.

An international approach for the synergistic case can lead to further reduction of nuclear fuel cycle investment. Figures 3.143 and 3.144 show that the international centres for reprocessing and recycling based on the economies of scale can enhance a transition to innovative fuel cycles by helping to overcome the investment barrier associated with reprocessing/recycling facilities. The economies of scale for large international centres lead to decreasing fuel cycle investments for the synergistic case up to 14% in the short term, up to 62% in the medium term, and up to 44% in the long term compared to the separate case. Total investments during the whole modelling period (2015–2100) become 46% less for the synergistic case. Discounting does not change the general results; although it slightly decreases the effect of investment savings for the synergistic case due to economies of scale (see Figs 3.145 and 3.146).

The comparison of cases is based on a simplified approach which assumes use of NOAK for fuel cycle facilities only. According to reported experience, FOAK plants are 15–55% more expensive than the subsequent serial units. In the period until around 2035, nuclear fuel cycle facilities can be available as FOAK plants so that investments can be increased for both cases (separate and synergistic).

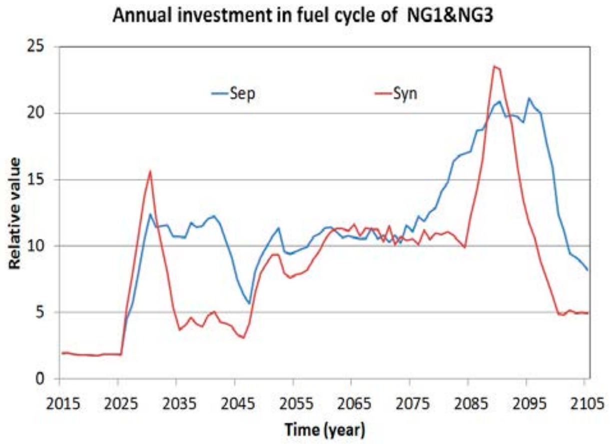


FIG. 3.141. Nuclear fuel cycle investments separate (N) versus synergistic (R) case.

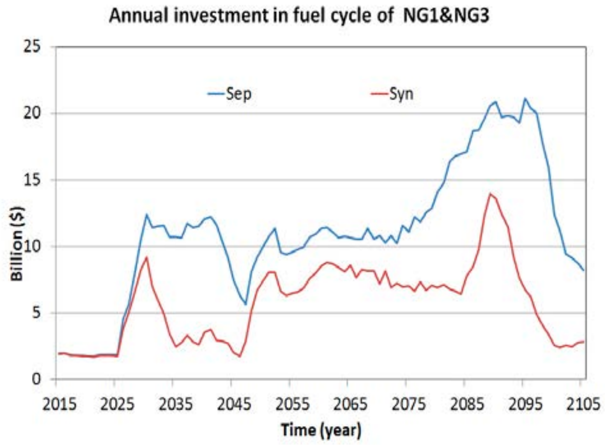


FIG. 3.142. Nuclear fuel cycle investments separate (N) versus synergistic (I) case.

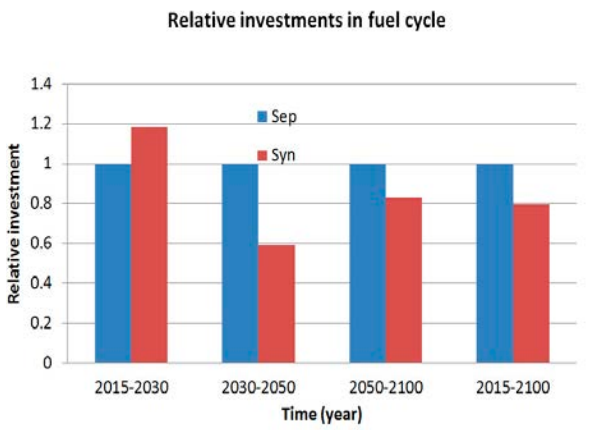


FIG. 3.143. Relative investments in fuel cycle for separate (N) and synergistic (R) cases.

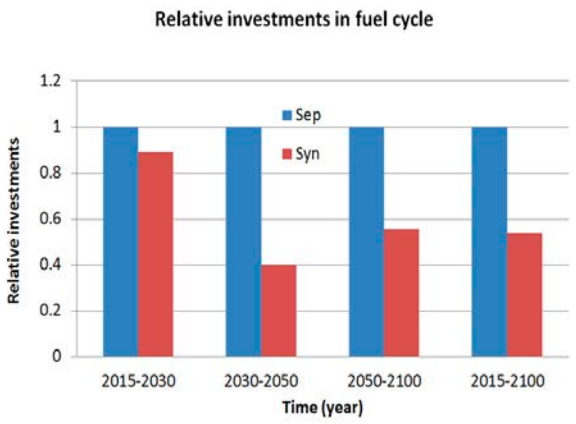


FIG. 3.144. Relative investments in fuel cycle for separate (N) and synergistic (I) cases.

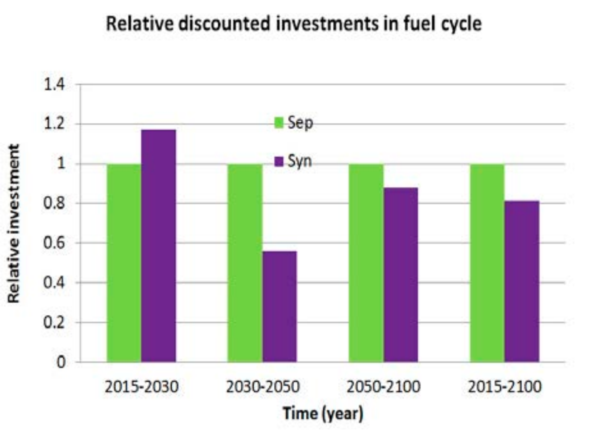


FIG. 3.145. Relative discounted investments in fuel cycle for separate (N) and synergistic (R) cases.

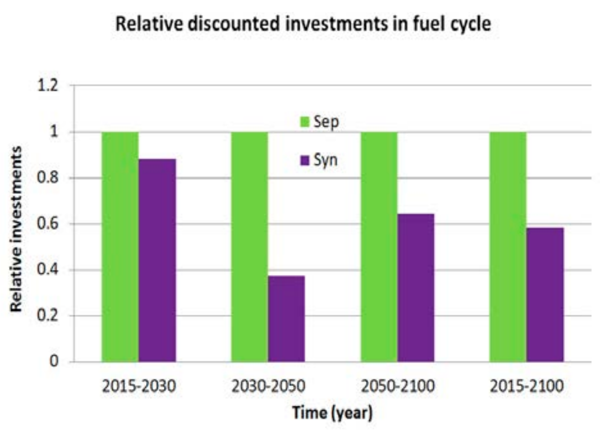


FIG. 3.146. Relative discounted investments in fuel cycle for separate (N) and synergistic (I) cases.

(a) Benefits in sharing of long term spent fuel storage facilities (R approach)

Another benefit of international cooperation in short term is related to the advantages of sharing long term spent fuel storage facilities. Figures 3.147 and 3.148 show the accumulation of UOX spent fuel in long term storage and associated relative investments in storage facilities for the separate case in NG1 and NG3. NG1 solves its issue of spent fuel accumulation by 2075 while investing only in the short term (2015–2025). NG3 steadily increases spent fuel accumulation, achieving more than 500 kt HM by the end of the century, while spent fuel storage in NG1 archives its maximum capacity of 160 kt HM by 2035. Investment in spent fuel storage for NG3 has a notable contribution to the total fuel cycle, especially after 2050.

In the synergistic case, the accumulation and relative investment pattern has much in common with the separate case in NG1 (see Figs 3.149 and 3.150). The spent fuel storage facility achieves its maximum capacity of 160 kt HM by 2035, then decreases and fully depletes around 2060. At that time, all LWR spent fuel available for reprocessing is reprocessed without accumulation in long term storage. The required investments in the short term are practically the same for the separate NG1. Figure 3.151 compares relative long term storage investments for the separate case versus the synergistic case that uses a reference (R) cost approach. Practically, identical storage capacities needed to store NG1 SNF in the separate case and NG1&NG3 spent fuel in the synergistic case, even in the R approach without counting economy of scale.

The above separate and synergistic scenarios include LWRs operating in a once through fuel cycle, fast reactors in a closed fuel cycle fuelled by its own reprocessed plutonium, and fast reactors fuelled by plutonium recycled from LWR spent fuel during its first three years in operation.

Figure 3.152 shows levelized fuel cycle unit cost with a discount rate of 5% for the LWRs and fast reactors considered in this study, calculated using the reference service cost (see Appendix II) for all fuel cycle steps. Fuel cycle components encompass uranium cost, reprocessing, fuel fabrication and waste management, as well as fuel for the first load of both reactor types. The fuel cost of fast reactors fuelled by their own reprocessed plutonium is comparable with the fuel cost of LWRs, while fast reactors fuelled by plutonium recycled from LWR spent fuel for first load and the first three operating years are about 50% more. This is caused by the much higher amount of spent fuel reprocessing needed to produce fuel for fast reactors from LWR spent fuel, in comparison to reprocessing fast reactor spent fuel with much higher plutonium content. Thus, the development of a fast reactor programme can face additional financial barriers at the first stage, as all new fast reactors have to pass through a stage of rather expensive fuel fabricated from LWR plutonium. The same issue was observed during investment analysis for the synergistic and separate cases. The reprocessing and recycling of LWR spent fuel may be a barrier to the implementation of closed fuel cycle based on LWRs and fast reactors.

An international centre for LWR spent fuel reprocessing is one possible way to discharges reduced reprocessing cost and to facilitate the overcoming of this barrier, as well as the reduction of fast reactor spent fuel reprocessing and MOX fuel fabrication. Figure 3.153 shows levelized fuel cycle unit cost at a discount rate of 5% for LWRs and fast reactors calculated using the international approach, with service cost based on 50% reduction of reprocessing/recycling costs (see Appendix II). In this case, levelized unit fuel cost (LUFC) of fast reactors fuelled by plutonium recycled from LWR spent fuel for the first load and first three operating years becomes comparable with the fuel cost of LWRs. Another factor that can change the situation in favour of fast reactors would be an increase in natural uranium costs. In turn, the LWR fuel component increases as uranium costs increase, whereas fast reactor fuel cost does not depend on natural uranium cost. Therefore, the international centre on reprocessing/fabrication can facilitate transition to an NES, based on fast reactors. Together with uranium cost increases, it can enhance the economic attractiveness of NES transition to fast reactors.

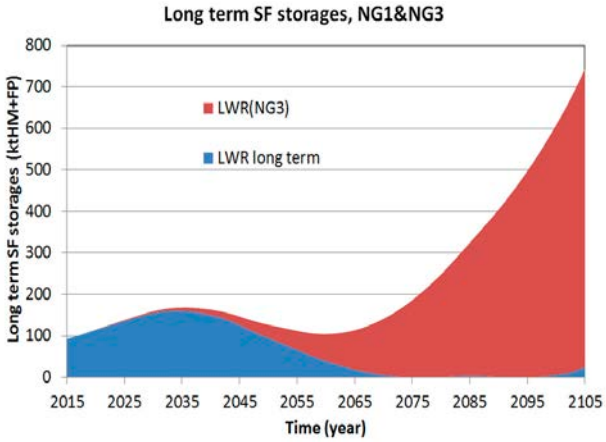


FIG. 3.147. Long term spent fuel storage facilities, separate case, NG1+NG3.

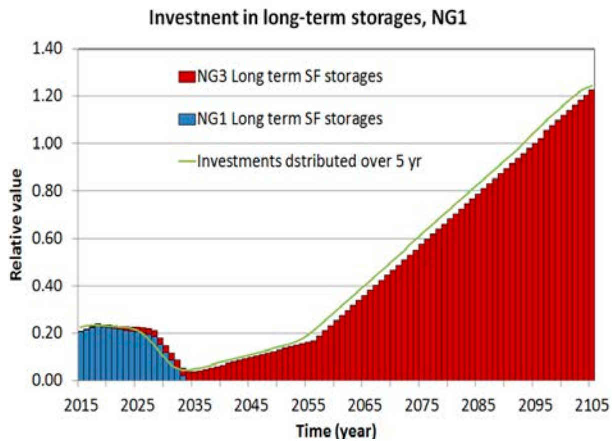


FIG. 3.148. Investments in long term storage facilities, separate case, NG1+NG3.

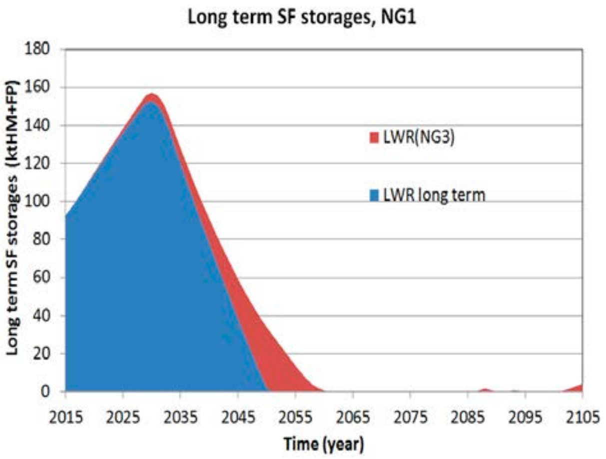


FIG. 3.149. Long term spent fuel storage facilities, synergistic case.

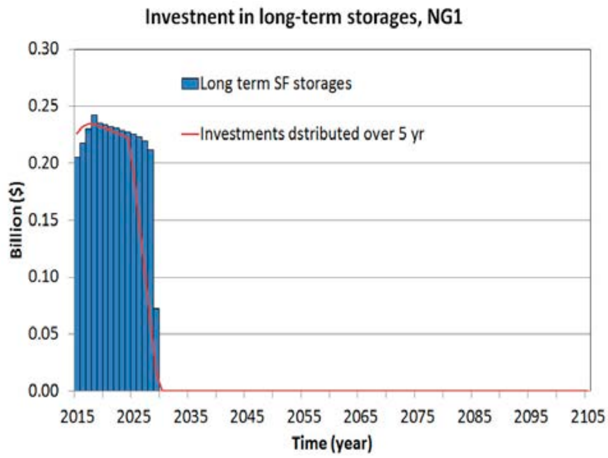


FIG. 3.150. Investments in long term storage facilities, synergistic case.

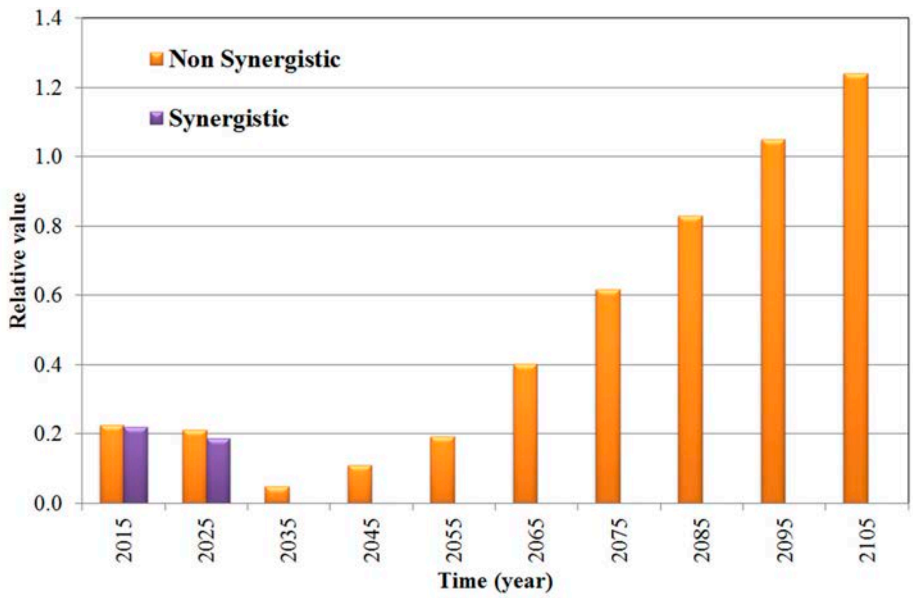


FIG. 3.151. Investments in long term storage facilities, separate case versus synergistic case.

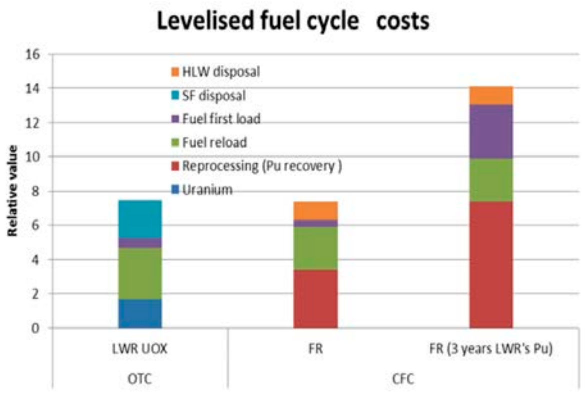


FIG. 3.152. Levelized fuel cycle unit cost, reference approach for service cost.

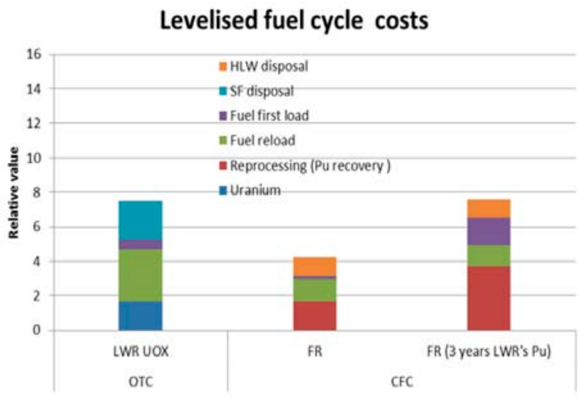


FIG. 3.153. Levelized fuel cycle unit cost, international approach for service cost.

3.3.5.5. Conclusions

The objective of the study is to show the relative difference between synergistic and separate (non-synergistic) cases using key indicators and investment cost in nuclear fuel cycles and LUEC. Investment indicators were used to verify the study results as LUEC discounts long term effects tending them to be flattened or nullified. Investment in the nuclear fuel cycle is an important component in the assessment of benefits and disadvantages of the various collaborative architectures as far as low fuel cycle cost is one of the nuclear power advantages and keeping fuel cycle cost low is an important factor of economic viability of nuclear power.

The study is based on the scenario approach developed in the GAINS project. The heterogeneous model for NG1, NG2 and NG3 groups of countries is the basis for assessment of the benefits and issues of cooperation between groups of countries (synergistic) and separate group development (non-synergistic). In the study, NG1 is assumed to provide 100% of the fresh fuel to NG3 and take back 100% of its spent nuclear fuel. Cooperation between technology holder (NG1) and technology user (NG3) countries affects the structure of electricity generation growth in NG1 which leads to the change in fuel cycle structure from mining to reprocessing.

The major contributors to the total fuel cycle investments are the spent fuel reprocessing and recycling in the short and long term and the enrichment in the medium term. The development of a fast reactor programme can face a significant financial barrier as far as at the first stage all new fast reactors have to pass through a stage of rather expensive fuel fabricated from LWR plutonium. Accounting of the economies of scale decreases the total fuel cycle investments for the synergistic case as compared to the separate case as follows:

- For the synergistic case, the decrease of fuel cycle investments can reach 14% in the short term, 52% in the medium term and 62% in the longer term, as compared to the non-synergistic case.
- The total investments during the entire modelling period (2015–2100) would be 46% less for the synergistic case.

Taking into account that a closed nuclear fuel cycle infrastructure development, as the study points out, may typically cost a few tens of billions of US dollars, the above mentioned savings are likely to make sense with respect to future generations.

Sharing of long term spent fuel storages is another examined option that may benefit from international cooperation in the short term. In the non-synergistic case, the accumulation of UOX spent fuel in the long term storage of NG3 will steadily increase achieving a significant amount by the end of century. Cooperation between NG1 and NG3 could resolve the issue of spent fuel accumulation in both groups of countries.

Calculation of the fuel cycle part of LUEC confirms the finding that an international centre on nuclear fuel reprocessing/fabrication could facilitate transitions to NESs based on fast reactors. Together with uranium cost increase, it can enhance the economic attractiveness of transitioning to fast reactor based innovative NESs.

The study quantitatively demonstrates that the synergistic approach to nuclear fuel cycle has a significant potential for offering a 'win-win' collaborative strategy to both, technology holders and technology users on their joint way to future sustainable NESs.

3.3.6. Sensitivity analysis of the shares of NG1/NG2/NG3 country groups in GAINS scenarios

3.3.6.1. Introduction

This study was performed within Task 1 of the collaborative project SYNERGIES, on the evaluation of synergistic collaborative scenarios of fuel cycle infrastructure development. Task 1 aims to provide a framework of scenarios for NESs, based on regional NES scenarios with and without collaborative agreements addressing fuel cycle options. Following the SYNERGIES objectives, the present study examines the role of collaboration among countries in making a transition to future sustainable NESs. The complete case studies can be found in Annexes XIV and XV on the CD-ROM accompanying this publication. Some intermediate results of the study were presented at the GLOBAL 2013 conference [3.81].

3.3.6.2. Objective and problem formulation

The objective of this sensitivity analysis is to study the behaviour of a global NES in terms of its key parameters and stress limits under variations in country group shares. The GAINS studies [3.52] were performed under fixed NG1:NG2:NG3 share ratio held at 40:40:20 (see Appendix IV). This study explores the possibility of transition of NG1 and NG2 groups under changes in NG1:NG2 proportion. The study also assesses the impact of NG3 share variation on NG1/NG2 front end and back end fuel cycle requirements.

The study also examines the impact of cooperation between NG1 and NG3 countries on the electrical power generation growth and nuclear fuel cycle structure of the NG1 countries. The sharing of long term fuel storage facilities sharing is also studied for short term prospects. The synergistic cooperation between NG1 and NG3 countries can also alleviate the problem of UOX spent fuel accumulation in long term storage facilities of NG3.

3.3.6.3. Assumptions, methods, codes and input data used

The study is based on the widely used and recommended framework developed in the INPRO GAINS collaborative project. The GAINS framework classifies non-personified countries into three country groups according to their nuclear fuel cycle strategies: NG1 countries pursue fast reactor programme and perform recycling of spent fuel; NG2 countries either directly dispose of the spent fuel or send it to NG1 for reprocessing; and NG3 countries are LWR based newcomer countries that send the spent fuel back to NG1 or NG2. The analysis methodology in this study is based on varying the allocation of future nuclear energy generation share of each country group as a function of time for assessment of different scenarios, in comparison to the GAINS studies where the NG1:NG2:NG3 ratio was kept fixed at 40:40:20.

The study assumes the high demand scenario established by the GAINS for nuclear power generation demand growth based on long term energy demand scenarios developed by the IAEA and the Intergovernmental Panel on Climate Change. According to the adopted high demand scenario, the energy demand grows to 5000 GW(e)·year in 2100 and flattens afterwards.

The base case is considered with three reactor types: LWR, HWR and fast reactor (breeding ratio of 1.0). A brief description of reactor characteristics used in the study is provided in Table 3.37. The fast reactors are assumed to replace LWRs gradually upon introduction. The share of HWRs in the nuclear energy mix is assumed to be constant at 6% and independent of fast reactor introduction.

Total fast reactor power generation rate is constrained at 10 GW(e)·year in 2030 and 400 GW(e)·year in 2050 in accordance with the high case scenario of the GAINS framework. Moreover, the total plutonium inventory is kept close to zero in the storage. The fast reactor introduction rate is not dictated by the GAINS framework after 2050, but is limited by available plutonium in the spent fuel and overall growth rate of nuclear power generation. Further assumptions used in the case study for NESs include: unlimited uranium resources; uranium enrichment tail assay at the 0.3% level; temporary spent fuel storage for HWRs; and spent fuel reprocessing with no heavy metal isotopes loss.

TABLE 3.37. REACTOR CHARACTERISTICS

	LWR	HWR	Fast reactor
Reactor electric output (MW)	1000	600	870
Efficiency (electricity) (%)	33	30	42
Av. load factor (%)	85	85	85
Plant lifetime (years)	60	60	60
Av. discharge burnup (GW·d/t)	45	7	65.9
Fresh fuel U enrichment (%)	4	0.711	—

The MESSAGE tool [3.36] was used for NES modelling for evaluating different energy development strategies under tailored constraints. The MESSAGE is an advanced NES modelling code developed at the IAEA which performs energy balances with minimal discounting costs and provides an optimized forecast of the energy evolution with required level of detail.

3.3.6.4. Summary presentation and analysis of the results

(a) Sensitivity analysis of world heterogeneous scenarios with different NG1 to NG2 shares

The impact of variation in NG1/NG2 shares keeping the NG3 share at the fixed value of 20% by 2100 on the front and back end fuel cycle and nuclear power structure is explored in this sensitivity analysis. The possible transition of group roles due to variation in the NG1/NG2 ratio is also considered. The following possible scenarios arise from the NG1/NG2 share in 2100:

(i) Minimum spent fuel: NG2 capacity share is low (10–25%). Maximum repocessing occurs in NG1.
(ii) High growth in NG1: NG1 observes nuclear power generation growth to 65% by 2100 from 50% in 2008.
(iii) Nominal case: Fixed NG1:NG2:NG3 ratio as 40:40:20 by 2100.
(iv) High growth in NG2: NG2 countries have power generation growth from 50% in 2008 to 65% by 2100.
(v) Minimum spent fuel reprocessing: Maximum spent fuel is handled by NG2 under low capacity share of NG1 (10–35%).

Figure 3.154 gives the annual consumption of natural uranium in the group of countries with moderate nuclear energy growth scenarios. There is no difference in annual uranium consumption between scenarios in the short or medium terms. In the long term, there are significant savings of uranium resources for options with a high share of NG1 and a low share of NG2. Maximum annual uranium consumption is about 500 kt U for Scenario 5 (minimal recycle, 10–35%) and 40% less (about 300 kt U) for Scenario 1 (minimal direct disposal, 10–25%). Therefore, the increase of the NG1:NG2 proportion due to transition from NG2 group to NG1 brings significant savings (up to 40%) in annual natural consumption in the long term. Synergistic and separate cases have nearly identical results, except for about 10% savings in the long term for Scenarios 1–3. The results for synergistic and non-synergistic cases are very close due to the small size of NG3 (20% of the world in 2100) and the fact that only half of NG3 spent fuel goes to NG1, while the other half goes to NG2, where it is not reprocessed. The difference between the non-synergistic and synergistic cases would be greater if the size of NG3 were larger and/or more of the NG3 spent fuel were to be sent to NG1, and/or if NG2 spent fuel were also to be exported to NG1 for reprocessing. These options will be explored below. The observation for synergistic and non-synergistic cases is in line with the GAINS reference heterogeneous cases. The high scenario shows similar behaviour.

Figure 3.155 shows total stored spent fuel, both at reactors and in storage facilities. The common trend for Scenarios 1 ‘Minimum SNF’, 2 ‘High growth in NG1’ and 3 ‘Base case’ is the reduction of stored fuel with slight differences between synergistic and non-synergistic cases. Scenario 4 ‘High NG2 growth’ shows a reduction of stored fuel for the separate case in the short, medium and long terms. In the synergistic case, the spent fuel from

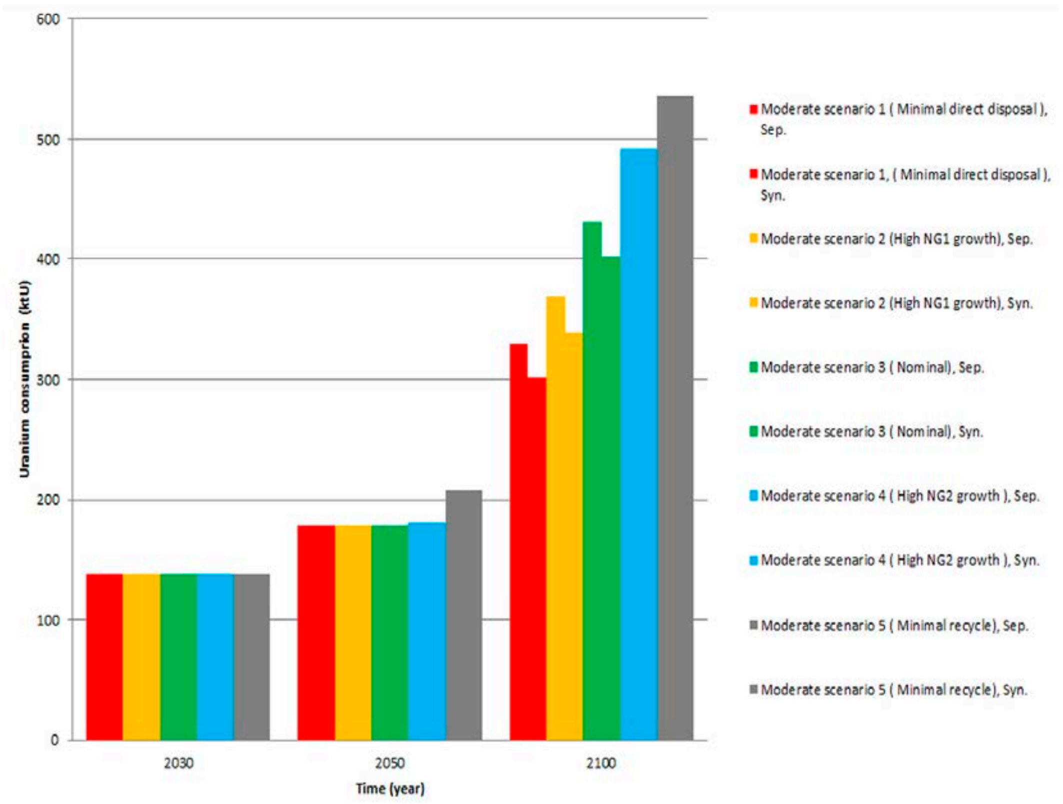


FIG. 3.154. Annual natural uranium consumption for NG1, NG2 and NG3.

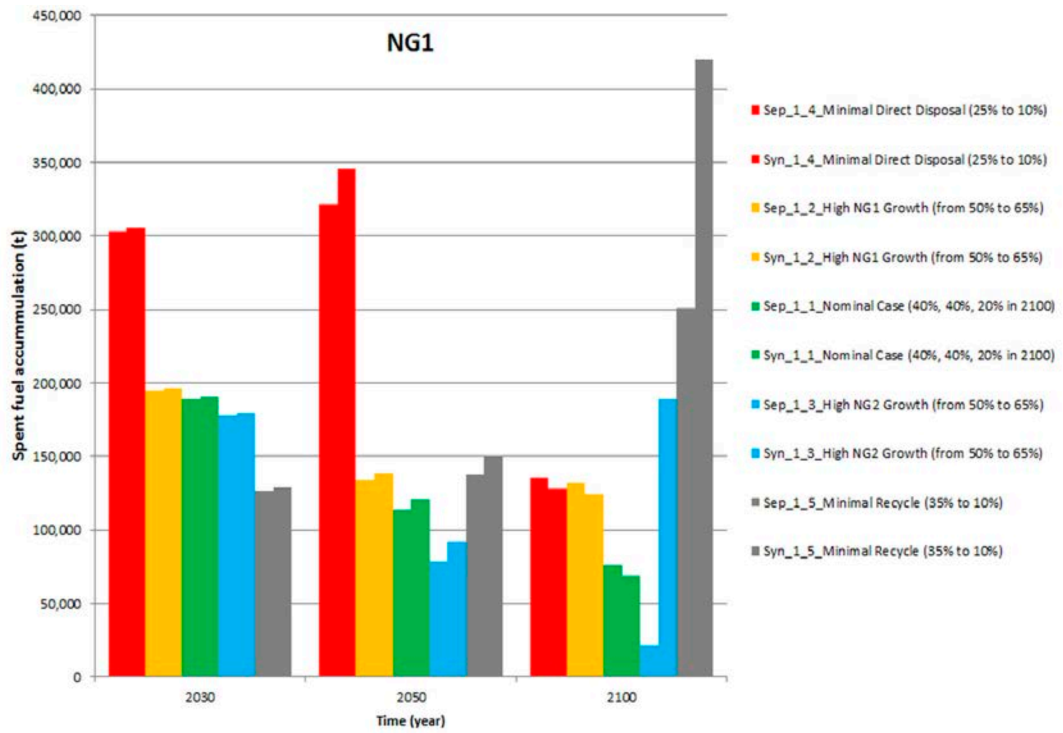


FIG. 3.155. Spent fuel accumulation in NG1, moderate case.

NG3 leads to more spent fuel accumulation in NG1 in comparison with the separate case, especially in the long term. The stressor impact of NG3 spent fuel is most significant for Scenario 5 'Minimum SNF reprocessing'. Accumulation of spent fuel is moderate in 2030 (125 kt) and is maintained until 2050; by 2100 there is 250 kt of spent fuel in NG1 (separate development) and 420.5 kt for the synergistic case.

For NG2, countries are developing and therefore the amount of spent fuel grows much faster for the synergistic case than for the separate case. The only fuel stored in NG3 is the small amount cooling at the reactors prior to shipment to NG1 and NG2.

Fuel stored in NG2 dominates the total storage, with the quantity of low burnup HWR fuel nearly matching the quantity of higher burnup LWR fuel due to all of the HWRs being in NG2. In the synergistic case, the only fuel stored in NG3 is the small amount cooling at the reactors prior to shipment to NG1 and NG2.

Figure 3.156 shows total stored spent fuel in all NGs at reactor pools and long term storage facilities. Spent fuel accumulation tends to increase as nuclear power growth in NG1 decreases from Scenario 1 'Minimum SNF' to Scenario 5 'Minimum SNF reprocessing' by 2100. The synergistic effect is rather small and begins to appear for Scenarios 1–3 by the end of the century. Scenarios 4 and 5 have no synergistic effects because NG3 spent fuel can be only partly reprocessed, with storing of spent fuel excess as discussed earlier. The high case gives similar results, with the synergistic effect appearing for Scenarios 1–4 due to more high room for fast reactor capacity growth.

In summary, there are significant savings of uranium resources and reductions of spent fuel for options with a higher share of NG1 and a low share of NG2 during a high growth scenario for nuclear energy. Spent fuel NG3 cannot be fully reprocessed in NG1 for scenarios with a low share of NG1 nuclear power. The synergistic effects are rather small and begin to appear by the end of century for scenarios with large or nominal growth of NG1 nuclear power.

(b) Sensitivity analysis of world heterogeneous scenarios with different NG3 shares

Fraction of nuclear power growth assigned to NG3 is varied for sensitivity analysis of the NG3 share in the global nuclear power structure, keeping the NG1 countries share constant at base case value of 40% (at 2500 GW(e)·year) in 2100. The study is conducted at different NG2/NG3 ratios of 50/10, 40/20 (base case scenario), 30/30, 20/40 and 10/50 in 2100. The results of power production growth in NG1 and NG3 under different NG3 market shares are shown in Fig. 3.157. In the analysis, the total demand curve follows the GAINS high demand case with 5000 GW(e)·year in 2100. Therefore, increase in NG3 share is a result of reduction in NG2 share.

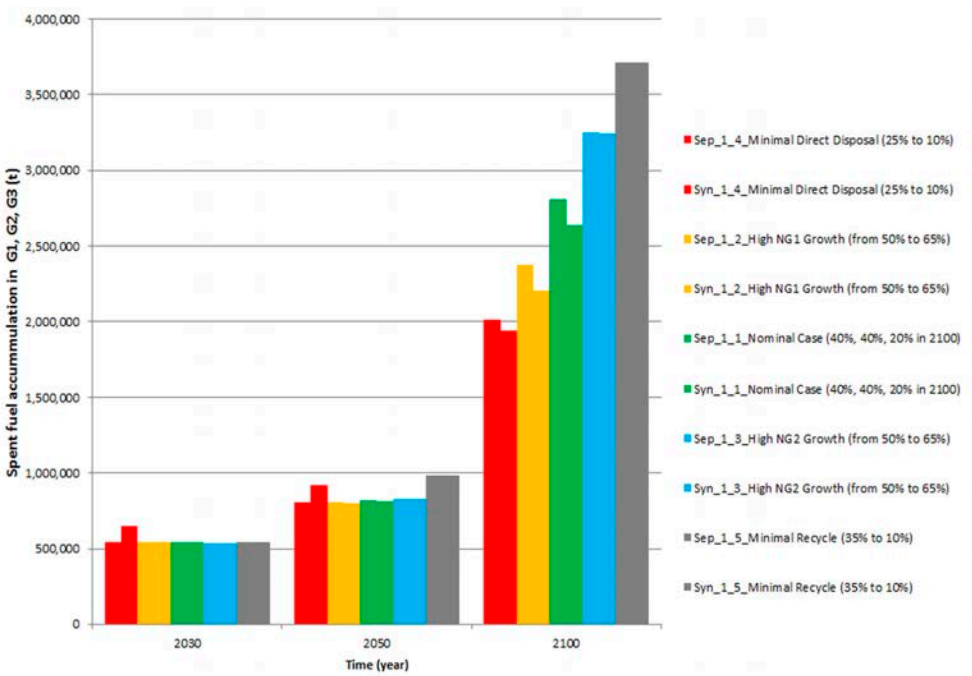


FIG. 3.156. Spent fuel accumulation in NG1, NG2, NG3, moderate case.

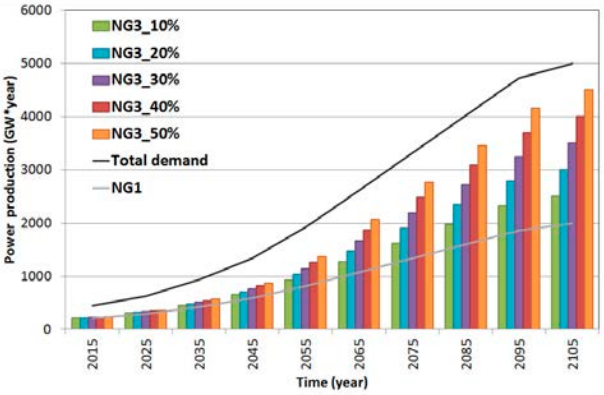


FIG. 3.157. Power production growth in NG1 and NG3.

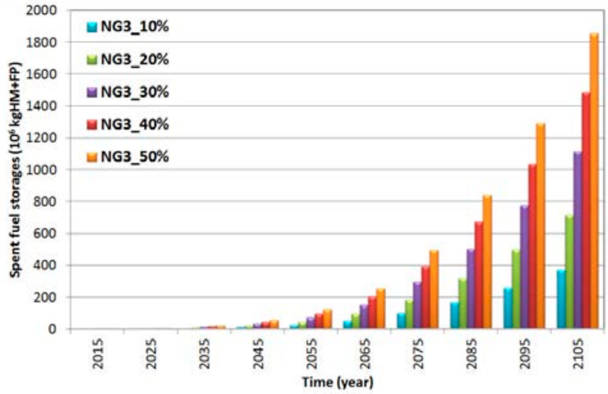


FIG. 3.158. Long term storage requirements in NG3.

(c) NG3 results on fuel cycle requirements for the non-synergistic and the synergistic cases

It is assumed that all NGs possess equal access to naturally occurring uranium all NGs contain their own front end and back end requirements of fuel cycle. In this case, assessment was carried out for fuel cycle requirements of NG3 and impact of synergistic cooperation between NG1 and NG3.

Spent nuclear fuel accumulation in NG3 long term storage facilities is shown in Fig. 3.158. The spent fuel long term storage in NG3 rises to 17 kt by 2050 and 300 kt by 2100 for NG3 shares of 10% and more severely it increases to 85 kt in 2050 and 1500 kt by 2100 for 50% NG3 share. Current global spent fuel accumulation in storage facilities stands at about 250 kt [3.82]. There is significant accumulation of plutonium and minor actinides in long term storage facilities that may lead to proliferation issues.

For the synergistic case, nuclear material exchange between NGs is permitted, which facilitates the NG countries to follow their preferred nuclear fuel cycle strategies. The NG3 group is assumed to follow a strategy of deploying LWRs with limited fuel cycle structure and relies on NG1 for the front end and back end fuel cycle services. In the synergistic case, NG3 countries can benefit by avoiding development and construction of own nuclear fuel cycle facilities or handling large inventories of dry spent fuel. The synergistic case does not require a dry storage facility at NG3 and spent fuel will be only placed in cooling pools of NG3 for initial cooling.

Handling and shipment of fresh and spent nuclear fuel among NG groups will be a concern in the synergistic scenario. Transported nuclear materials may be handled as Category 3 with fresh fuel having only low enriched uranium and spent fuel sealed in radiation barrier as described by the GAINS framework.

(d) Impact of NG3 share on the NG1 nuclear fuel cycle

In the synergistic case, increase in NG3 share will lead to increased availability of material for fast reactors of NG1, since NG1 is responsible for providing all fresh fuel to NG3 and taking back entire spent fuel of NG3. Power production growth curves of fast reactors and LWRs in NG1 for the synergistic case are shown in Figs 3.159 and 3.160, respectively.

Significant impact of NG3 share on power production structure of NG1 is observed in the medium and long terms. The fast reactor power production growth in NG1 becomes significant after 2050 and reaches 1300–1900 GW(e)·year level in 2100 for NG3 share of 10–50%. The power production growth of LWRs in NG1 increases to a level above 900 GW(e)·year for the non-synergistic case but reduces to almost zero in the synergistic case by 2100 in the synergistic case with 50% share of NG3. There is no impact of change in NG3 share on NG1 power structure in the short term, which will be explained in subsequent section. Change of NG1 power production structure induces certain changes in nuclear fuel cycle infrastructure of NG1.

The increase in NG3 share impacts on NG1 fuel cycle capacities and cumulative uranium requirements due to the increasing services provided for LWR in the NG3 group. Moreover, with increased NG3 share, MOX fabrication capacity for fast reactors will increase. Therefore, the fuel cycle infrastructure and capacities in NG1 should be significantly upgraded (see Fig. 3.161). Development of large scale facilities would benefit NG1 in the collaboration. All facilities including reprocessing is considered to operate at a full capacity. There is limitation at

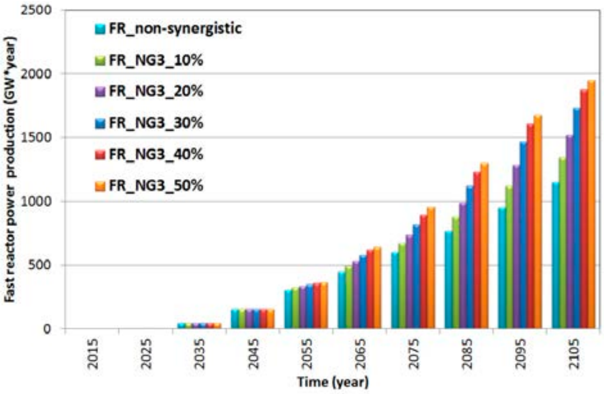


FIG. 3.159. Fast reactor power production growth in NG1.

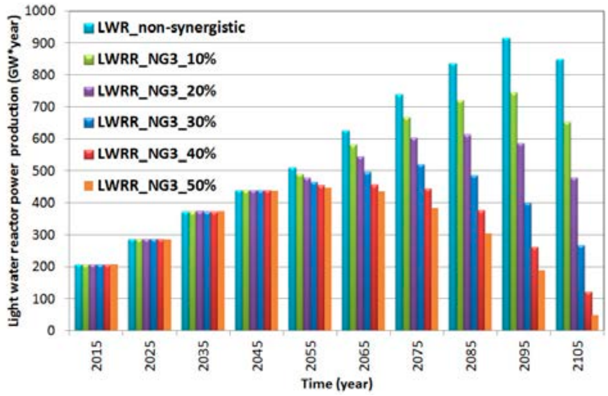


FIG. 3.160. Light water reactor power production growth in NG1.

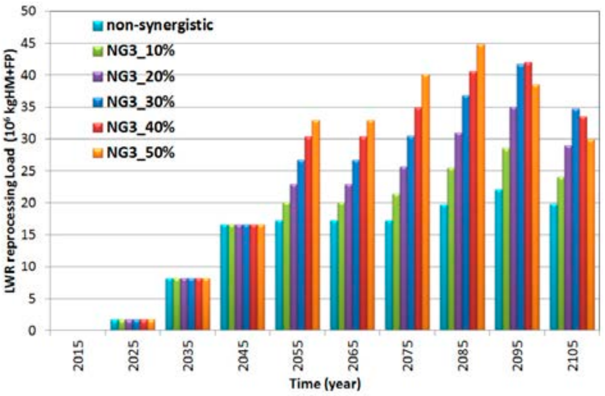


FIG. 3.161. Light water reactor fuel reprocessing capacities in NG1.

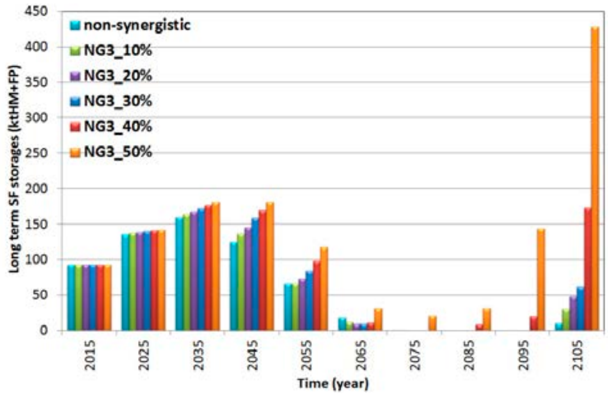


FIG. 3.162. Light water reactor long term spent fuel storage facilities in NG1.

850 t/year on introduction of LWR reprocessing capacity until 2050. This limitation leads to the same recovered plutonium for all NG3 share and consequently the same number of introduced fast reactors, and same amount of discharged spent fuel.

The long term spent fuel storage requirements at NG1 shown in Fig. 3.162 constitute spent fuel from both NG1 and NG3 for the synergistic case. The spent fuel inventory vanishes in around 2075 for 10–40% share of NG3, but starts to accumulate again since the reactors commissioned after 2030 start to decommission and new fast reactor installation is limited by total nuclear demand growth. Full core discharge of decommissioned reactors can be reprocessed to supply additional plutonium for loading in new fast reactors.

Available spent fuel inventory is not completely used up for NG3 share at 50%. It decreases to 20 kt in the medium term but increases back due to limitation on installation of new fast reactors by overall demand growth capacity in NG1. Nevertheless, the long term storage requirements of spent fuel are considerably reduced in the synergistic cooperation approach. Fast reactor spent fuel is not accumulated in the long term storage, since it is moved to reprocessing soon after cooling. The minor actinide accumulation is increased in NG1 with an increase in NG3 share in the long term. Minor actinide stock of NG3 reaches 10–30% of total accumulation of minor actinides in NG1 by 2100.

(e) Impact of NG3 and NG2 on NG1 nuclear fuel cycle

The previous cases did not consider nuclear material transfer between NG1 and NG2. NG2 countries follow the NFC strategy to either dispose of spent fuel or send it abroad for recycling. Synergistic cooperation between NG1 and NG2 can provide a solution to the global spent fuel accumulation problem and associated waste disposal issues.

In this study, base 1 case is analysed for the scenario in which all spent fuel reprocessing of NG2 and NG3 takes place at NG1 along with its own spent fuel. It is observed that all LWRs in NG1 are replaced by fast reactors after 2040. The fast reactor power production is also increased due to added supply of plutonium from NG2 spent fuel, being 30% more when compared to using spent fuel from NG3 only. This leads to significant impact of NG2 on NG1 nuclear power structure, with fast reactor introduction in NG1 increasing by 63% in medium term and by 38% in the long term when compared with NG1–NG3 synergy scenarios (see Fig. 3.163).

Reprocessing load is shown in Figs 3.164 and 3.165 for scenario of shipping NG2 and NG3 spent fuel to NG1 and scenario of returning only NG3 spent fuel to NG1, respectively for comparison among these cases. There is significant difference in both scale of reprocessing and structure of reprocessing in medium and long terms for both cases. The NG2 spent fuel reprocessing is limited due to constraint on reprocessing capacity set at maximum value of 850 t/year till 2050 and 3000 t/year of spent fuel afterwards. The limit on maximum capacity of reprocessing was increased to 3000 t/year after 2035 for the case of NG2 spent fuel transport to NG1 as compared to the 2050 t/year limit in the NG3 spent fuel return case. The reprocessing load at NG1 increases to 33 t/year initially but starts declining after 2045 to almost zero by 2100 for the NG1–NG2–NG3 synergistic case.

The reprocessing load of fast reactor fuel is also affected by the NG2 spent fuel. The separation and reprocessing requirements of fast reactor fuel increase on introduction of more fast reactors as more spent fuel is available from NG2 countries. Thus, a significant impact of NG2 spent fuel is observed on both LWR and fast reactor fuel reprocessing capacities.

Long term storage requirement of LWR spent fuel in NG1 is provided in Fig. 3.166, which shows that NG2 spent fuel could not be completely utilized. The NG2 spent fuel inventory first reduces to 200 t by 2065 but

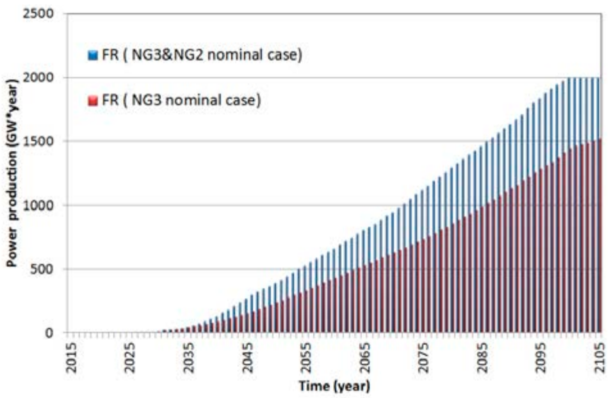


FIG. 3.163. Comparison of Fast reactor power production growth (NG3&NG2 and NG3 impact).

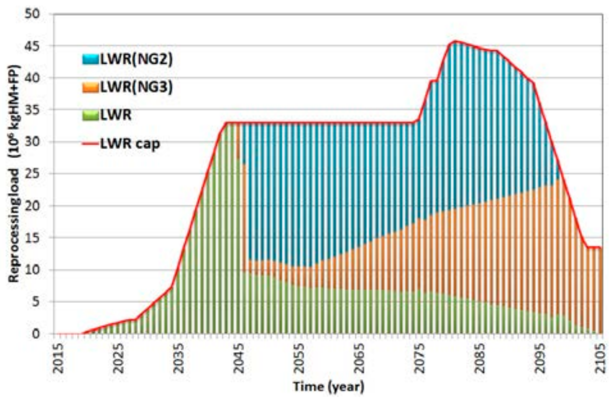


FIG. 3.164. Light water reactor reprocessing load (NG3 and NG2 impact).

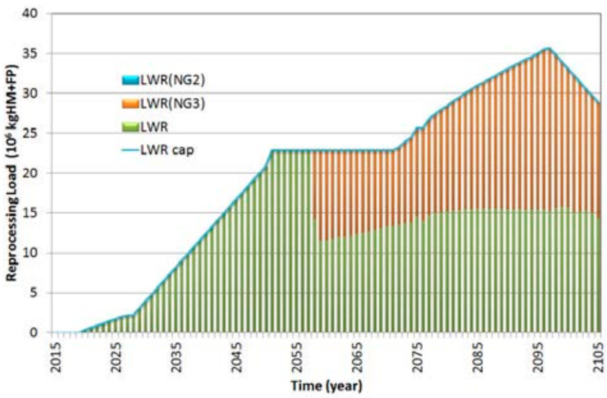


FIG. 3.165. Light water reactor reprocessing load (NG3 impact).

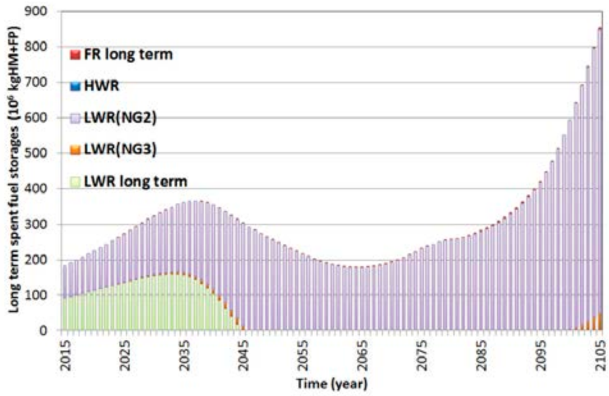


FIG. 3.166. Light water reactor long term storage in NG1 (NG3&NG2 impact).

increases afterwards due to increased LWR spent fuel requirement by NG1 for constructing maximum fast reactors. Further introduction of fast reactors is limited by total power demand limit of 2000 GW(e) in year 2100 in NG1.

Reprocessing rate and nuclear power demand of NG1 play an important role in the fast reactor introduction rate and NG1 reprocessing capability of spent fuel from other NGs. Under the aforementioned cases, a part of spent fuel from NG2 and/or NG3 has to be stored or disposed of. Spent fuel accumulation would further worsen on increasing the breeding ratio of fast reactors. One of the approaches to alleviate this issue is to introduce new fast reactors in NG2 and/or NG3 without an associated fuel cycle. Another solution is to increase the NG1 share in the global energy mix to allow the introduction of more fast reactors. A special case was considered which could quantify NG1 power demand to completely resolve global spent fuel accumulation problem. The high growth scenario in NG1 was assumed with demand level at 50–65% of the world power demand (3250 GW(e) in 2100). This case completely consumes spent fuel from all NG sources by 2070. Hence in this case, spent fuel from NG2 and NG3 can act as a resource for NG1 for global transition to large scale nuclear energy without spent fuel accumulation issues.

(f) Natural uranium cost perspective

Based on the uranium data provided in Annex XIV, natural cost outlook for high global demand was estimated. Results for different fuel cycle and collaboration strategies are presented in the Fig. 3.167. In the business as usual (BAU) scenario, all identified and undiscovered resources of various costs that comprise 17.5 are exhausted by 2069. The transition from the BAU approach to the BAU–fast reactor separate approach would lead to a shift of approximately four years, to 2073. Collaboration with NG3 shifts the time at which identified and undiscovered resources are exhausted to 2076. Collaboration among NG2 and NG3, together with high NG1 growth, adds an additional four years and shifts the exhaustion of identified and undiscovered uranium to 2080. In total, the maximum shift of the time at which identified and undiscovered resources are exhausted is about ten years. Thus, in the short term, the transition from a BAU option to the BAU–fast reactor synergistic option does not provide the needed impact on uranium cost in the high scenario, and results in shifting the exhaustion of identified and undiscovered resources to about ten years in the medium term. All countries can benefit from longer lasting lower costs of natural uranium in the long term.

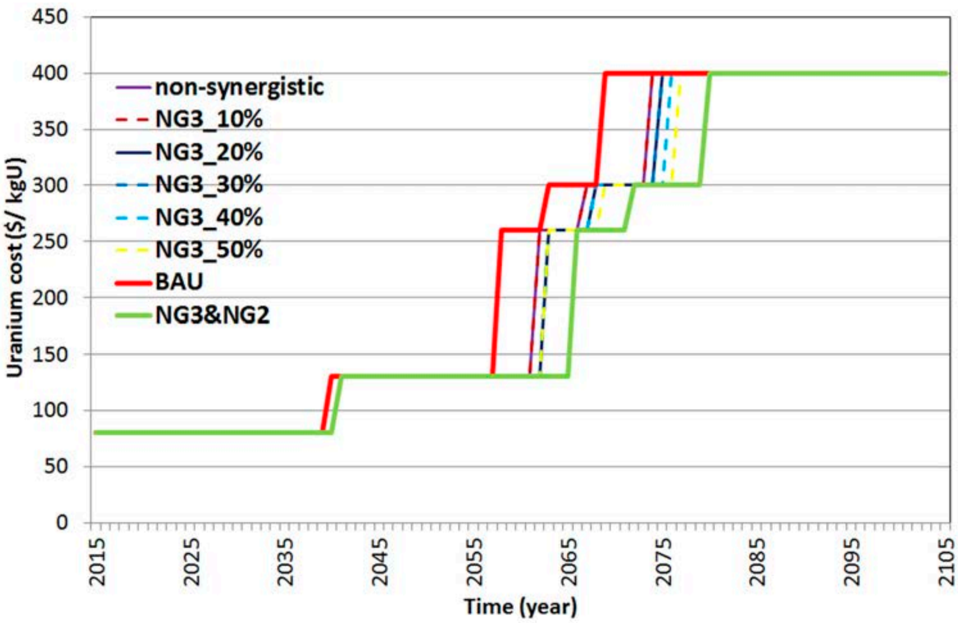


FIG. 3.167. Natural uranium cost perspective versus uranium exhaustion.

3.3.6.5. Conclusions

This sensitivity study was focused on determining the impact on key parameters of NESs due to changes in group shares of three country groups following different nuclear fuel cycle strategies — namely, NG1 (technology holders), NG2 (technology users) and NG3 (newcomers) — using the GAINS framework. The GAINS studies had a nuclear share ratio of NG1:NG2:NG3 fixed at 40:40:20. Changes in NG1:NG2 considers possibility of transition of group roles between these groups. Possible market share of NG3 countries is considered by variation of the NG3 share.

For the high energy growth scenario, high NG1 share and low NG2 share are observed to induce significant improvement in uranium resources utilization and spent fuel inventory reduction. Low NG1 share cases cannot fully utilize spent fuel coming from NG3 countries. NG3 spent fuel can be handled at NG1 in the synergistic case with minimal impact on nuclear fuel cycle infrastructure of NG1. However, the benefits of synergy between NG1 and NG3 are small for NG3 share below 20% and become noticeable only by the end of the century for high or nominal NG1 share.

NG3 share at higher limits of above 40% causes stresses in NG1. Complete reprocessing of NG3 spent fuel cannot take place despite having sufficient fuel reprocessing capacity at NG1 since fast reactor introduction is limited by overall demand growth rate for NG1. On the other hand, significant reduction in long term spent fuel storage requirement is achieved by such synergistic cooperation.

In synergistic cooperation between NG1, NG2 and NG3 countries, spent fuel accumulation is observed with stresses in NG1. Overall power demand growth and reprocessing rate of NG1 limit the fast reactor introduction rate and NG1 reprocessing capability of accumulated spent fuel from all NGs. A part of spent fuel from NG2 and NG3 has to be stored and/or disposed of at their own facilities. Increasing the breeding ratio of fast reactors at NG1 will further intensify the spent fuel accumulation issue. The problem can be resolved by fast reactor introduction in NG2 and/or NG3 without the associated fuel cycle.

Considering high energy demand growth and improved reprocessing capacities at NG1 can completely consume spent fuel from NG2 and NG3 by 2070, thus providing a valuable solution to global spent fuel accumulation issue using appropriate global synergistic collaboration options.

The investigation from the uranium cost perspective shows that the transition from a BAU option to a BAU–fast reactor synergistic option does not have a large impact on uranium cost in the high scenario in the short term, but it does push the depletion of the identified and undiscovered uranium resources about ten years forward in the medium term. All countries can benefit from longer lasting low costs of natural uranium in the long term.

3.3.7. Alternative deployment strategy of fast reactor startup on enriched U fuel

3.3.7.1. Introduction

The present study was performed within Task 2, on the evaluation of additional options for NESs with thermal and fast reactors of the collaborative project SYNERGIES. The objective of this task is to investigate possible synergies among the already considered technology options and additional options which have not been addressed in previous INPRO studies. The GAINS analytical framework [3.52] was a basis for the performed studies. This framework considers a global scenario level for NESs based on regional NES scenarios with collaborative agreements addressing fuel cycle options. Based on SYNERGIES objectives, this study considered various fast reactor deployment strategies for sustainable global nuclear energy in the 21st century. The complete case studies can be found in Annexes XVIII and XIX on the CD-ROM accompanying this publication. Some intermediate results of study were presented at the HLMC 2013 conference [3.83].

3.3.7.2. Objective and problem formulation

One of the problems with the current generation of nuclear fuel cycles based on thermal reactors is the limited supply of natural uranium that can be obtained economically. Natural uranium is used inefficiently within the existing once through nuclear fuel cycle and is not available equally to all countries. Moreover, large scale nuclear power reactors operating in a once through nuclear fuel cycle cannot be deployed at the same capacity as organic fuelled power plants.

Addressing the uranium fuelling problem requires modelling the long term scenarios for nuclear power development in order to predict the consequences of various approaches. In this context, proposals to develop nuclear power on a large scale focus on the use of fast reactors instead of thermal reactors. This study describes and tries to explain that it is more efficient and effective to use enriched uranium in a fast reactor (breeding ratio > 1) and recycle its spent fuel to extract plutonium for further use than to use enriched uranium in LWRs (breeding ratio < 1) without further recycling.

This study provides more detailed analysis of the likely impacts of introducing fast reactors with enriched uranium fuel. The findings are then applied to the GAINS project analysis of a synergistic heterogeneous world model [3.52], taking into account material flow analysis and economics: material flow analysis considers natural uranium consumption, SWU, plutonium balance in the storage, and spent fuel; economics considers fuel cost analysis and levelized fuel cycle unit cost associated with different reactor types.

3.3.7.3. Assumptions, methods, codes and input data used

Two growth curves were established for GAINS, as follows: a high case that climbs to 5000 GW(e)·year and a moderate case that climbs to 2500 GW(e)·year being flattened after 2100. Each curve has three growth periods and follows a linear growth to meet the specific level of power generation by the end of the respective period:

(i) 2009–2030: 600 GW(e)·year and 700 GW(e)·year growth levels for the moderate and high case, respectively.
(ii) 2031–2050: 1000 GW(e)·year and 1500 GW(e)·year growth levels for the moderate and high case, respectively.
(iii) 2051–2100: 2500 GW(e)·year and 5000 GW(e)·year for the moderate and high case, respectively.

Four reactor types have been considered: LWR, HWR and two fast reactors, FR12_MOX and FRU. FR12_MOX reactor is an SFR (breeding ratio of 1.2) using MOX fuel. FRU uses enriched uranium fuel for first startup with subsequent recycling of plutonium+uranium+minor actinides from the spent fuel. FRU could be, for example, a lead cooled fast reactor design with a breeding ratio of 1.05. Calculations were carried out using MESSAGE [3.36], CYCLE [3.84] and the IAEA NEST tool for economic aspects (i.e. LUEC). Following the GAINS approach, several assumptions also were implied on reactor and fuel cycle features:

— Unlimited uranium resources are assumed.
— The uranium enrichment tails assay is equal to 0.3% for models in Annex XVIII and 0.2% for models in Annex XIX.
— Temporary storage is used for HWR spent fuel.
— Cooling pool retention time is three years for irradiated fast reactor fuel assemblies, five years for irradiated LWR fuel assemblies.
— The loss factor of the fuel fabrication and reprocessing is equal to zero.

A fast reactor with a first loading (FRU) of enriched uranium was introduced in the basic fuel cycle system of GAINS framework (see Fig. 3.168).

3.3.7.4. Summary presentation and analysis of the results

(a) Alternative fast reactor deployment scenarios of transition to sustainable NESs (^{235}U load versus uranium–plutonium load)

For fast reactors, an alternative use of enriched uranium fuel for first startup with subsequent recycling (of plutonium+uranium+minor actinides) from the spent fuel is an interesting option. This option was addressed briefly in Ref. [3.25]. This study provided more detailed considerations for the impact of introducing fast reactors with enriched uranium fuel startup.

Figures 3.169–3.172 present comparison of key characteristics of considered reactor types for detailed understanding of scenario simulation. Total natural uranium consumption for first load and total annual reload over the life of reactor is compared in Fig. 3.169. LWRs have the highest natural uranium consumption total during

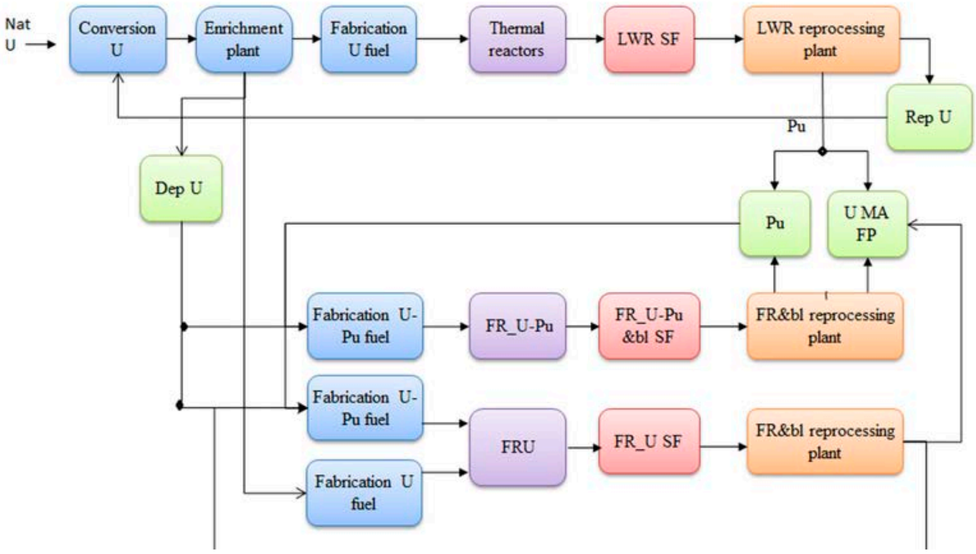


FIG. 3.168. Fuel cycle system, BAU with fast reactor scenario.

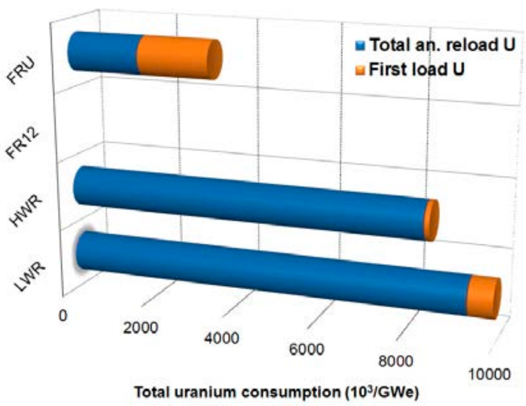


FIG. 3.169. Total uranium consumption.

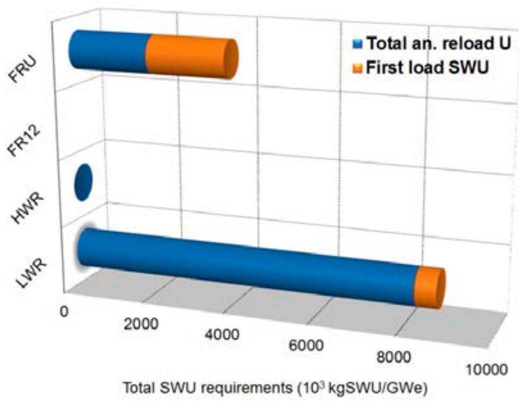


FIG. 3.170. Total separative work unit requirements.

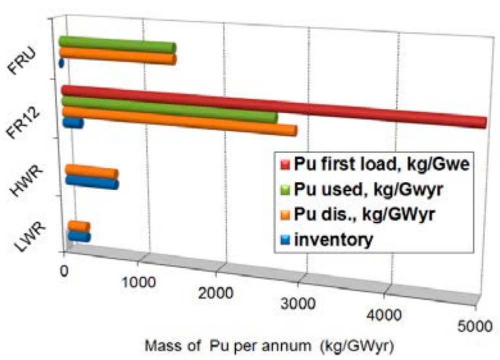


FIG.3.171. Mass of plutonium per year.

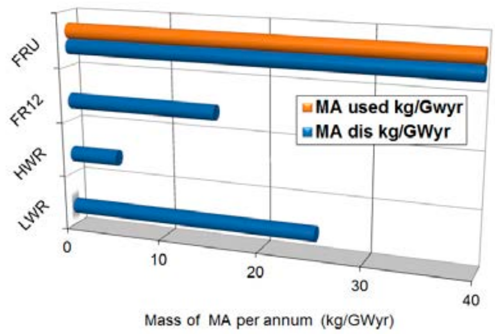


FIG. 3.172. Mass of minor actinides per year.

lifetime and FRU has the lowest uranium consumption in the form of enriched uranium. Therefore, replacing LWRs by fast reactors can lead to potential saving of natural uranium resources. Similar trends are shown by the Fig. 3.170 in terms of total SWU requirements. Figure 3.171 shows the comparison of the plutonium ‘inventory’, which is a difference between production and consumption of plutonium for the typical reactor type. Figure 3.172 shows a comparison of minor actinide production over the life of the reactors.

There are constraints imposed by the GAINS framework on total power production rate of fast reactors by 2030 and 2050, with objectives in high growth case to have total fast reactor generation rate of 10 GW(e)·year in 2030 and a total of 400 GW(e)·year in 2050. The GAINS framework also puts constraint on total plutonium inventory in the spent fuel storage to be maintained close to zero. Fast reactors introduction rate after 2050 is not constrained by the capacity, but rather limited by plutonium availability and overall growth rate of the NES.

The analysis shows that available industrial reprocessing capacity significantly lacks the plutonium production to satisfy the fast reactor introduction rate. Limited reprocessing capacity will reduce the introduction rate of fast reactors, which needs to be considered in efficient planning of long term global transition scenario towards fast reactors.

The study further investigates the impact of limiting LWR reprocessing capacity on possible deployment of fast reactors. Figures 3.173 and 3.174 show the curves for power production growth demand of fast reactors as identified by GAINS (linearly growing to 400 GW(e)·year by 2050) and related demand reprocessing load. With unlimited separation capacity, it results in significant reprocessing requirements for a very short period of about 1–3 years in 2030 and 2050 for the first fast reactor fuelling.

Fast reactors require an operational time of three years prior to start using plutonium reprocessed from their own spent fuel. Many reprocessing facilities cannot be built in a limited duration of few years due to economic constraints. Figures 3.173 and 3.174 also show that a power production growth rate of 400 GW(e)·year for fast reactors can be achieved if the introduction of new reprocessing capacities is limited to 850 t HM/year of LWR spent fuel until 2050 and up to 3000 t HM/year of LWR spent fuel afterwards. Whereas, limiting new LWR reprocessing capacity introduction to 850 t HM/year results in only 300 GW(e)·year power production capacity realization. Hence, the limitations in reprocessing capacity pose a considerable limit on the fast reactor deployment. If the reprocessing capacity introduction limit is elevated to 3000 t/year of spent fuel after 2035, LWR spent fuel reprocessing can be increased and 400 GW(e)·year fast reactor power growth can be achieved by 2050. However, the demand will not be met by linear growth of fast reactors in this case. This issue can be overcome by using enriched uranium as first fuel loading in fast reactors.

This study employs the GAINS framework for assessing impact of different reactor types on infrastructure requirements of nuclear fuel cycle over time. The study considered SFRs and LFRs, first loaded with enriched uranium and subsequently shifting to their own plutonium based reprocessed fuel. The study aims at identifying the prospects and limitations of deployment strategies of different fast reactors and their combinations. The sensitivity of fast reactor shares towards different key indicators of the NES is evaluated. Following possible options with mentioned fast reactor shares are evaluated in the current study:

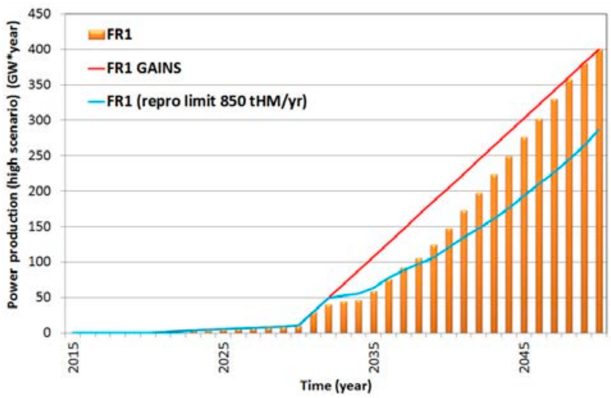


FIG. 3.173. Fast reactor power production growth.

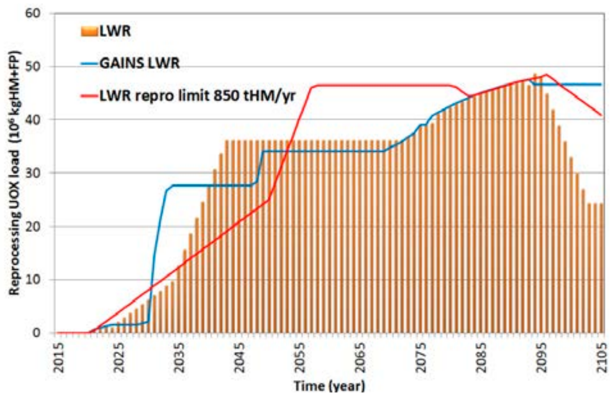


FIG. 3.174. Reprocessing rates for UOX fuel.

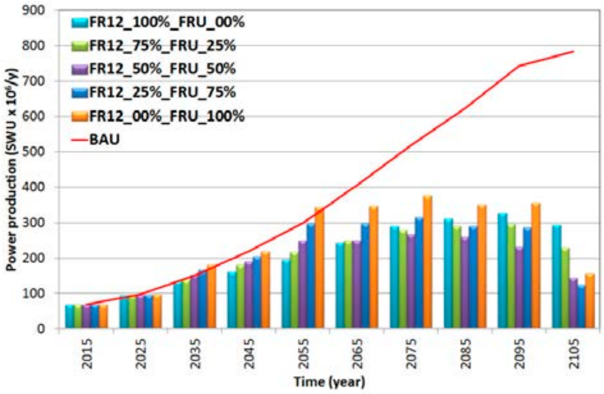


FIG. 3.175. Fast reactor power production growth.

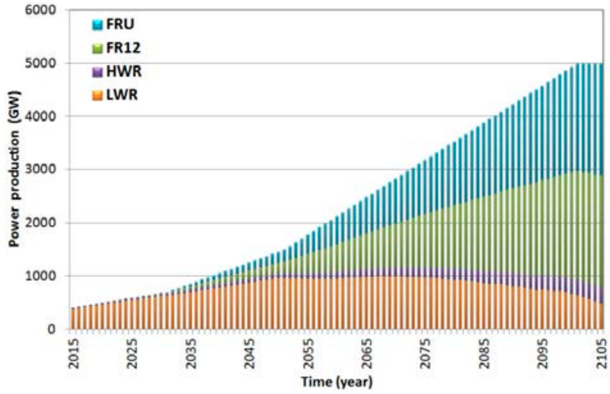


FIG. 3.176. Power production growth (FRU: 50% of fast reactor power production growth).

— BAU: Once through nuclear fuel cycle using conventional LWRs and HWRs.
— FR12_00%/FRU_100%: FR12 at 0% and FRU at 100% share of total fast reactor demand.
— FR12_25%/FRU_75%: FR12 at 25% and FRU at 75% share of total fast reactor demand.
— FR12_50%/FRU_50%: Both FR12 and FRU at 50% share of total fast reactor demand.
— FR12_75%/FRU_25%: FR12 at 75% and FRU at 25% share of total fast reactor demand.
— FR12_100%/FRU_00%: FR12 at 100% and FRU at 0% share of total fast reactor demand.

Figure 3.175 shows the fast reactor power production growth for different shares of fast reactor types varying from 0% to 100%. Figure 3.176 shows overall global power production growth for a case of both FRU and FR12 shares at 50% of fast reactor nuclear power demand. Total fast reactor demand is set initially at 400 GW(e)·year by 2050 and at maximum possible fast reactor introduction rate afterwards.

Different fast reactor share options are analysed and compared with the BAU option for the key indicators of NES such as cumulative natural uranium utilization, SWU requirements, LWR spent fuel reprocessing requirements, spent fuel accumulation in dry storage facilities, reprocessed fission products and minor actinide stocks, plutonium and minor actinide accumulation in long term spent fuel storage facilities. Figures 3.177 and 3.178 show cumulative natural uranium consumption for the considered options and comparative performance of these options to the BAU scenario, respectively.

All options of fast reactor shares show similar saving of natural uranium in the long term perspective, with option of FR12_50%/FRU_50% performing slightly better. However, completely different trends are observed in short and medium terms. The highest natural uranium consumption is observed with the FR12_00%/FRU_100% option until 2060 and this trend is even higher than the BAU option rising 5% above it from 2035 and 2040. The lowest natural uranium consumption is observed with the FR12_100%/FRU_00% option until 2070. The FR12_50%/FRU_50% option shows intermediate natural uranium consumption in the medium term lying close to the FR12_100%/FRU_00% option, which is justified since there are significant requirements of natural uranium for first enriched uranium core loading of FRU reactors (see Fig. 3.169).

Annual SWU requirements calculated for different fast reactor share options are shown in Fig. 3.179. The SWU requirements for the BAU case are comparable with other fast reactor share options in the short (until 2030) and medium (until 2050) terms, but considerably higher than all fast reactor options in the long term rising to 800 kt SWU/year by 2100. Two relatively short lived steep SWU growth trends are observed for the FRU options around 2030 and 2050 resulting from the increase in capacity growth rate of FRUs. The most noticeable rise in SWU requirements from 220 kt SWU/year to 350 kt SWU/year is observed for the FR12_00%/FRU_100% option in 2050, but straightens afterwards to the end of the century. Most feasible results are obtained from the option of FR12_50%/FRU_50% which shows nominal growth in 2050 and minimal level of SWU requirements for the medium and long terms, thus being the optimum choice among all fast reactor share options.

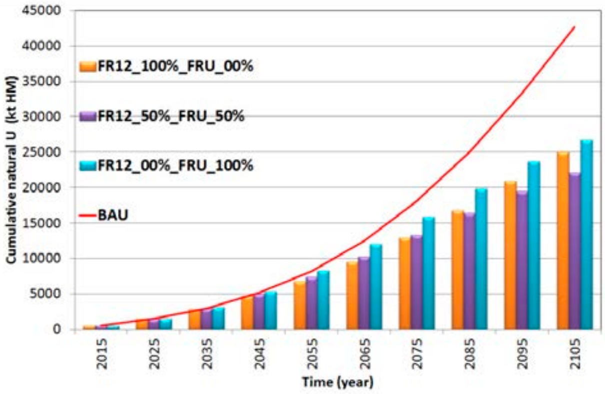


FIG. 3.177. Cumulative natural uranium consumption.

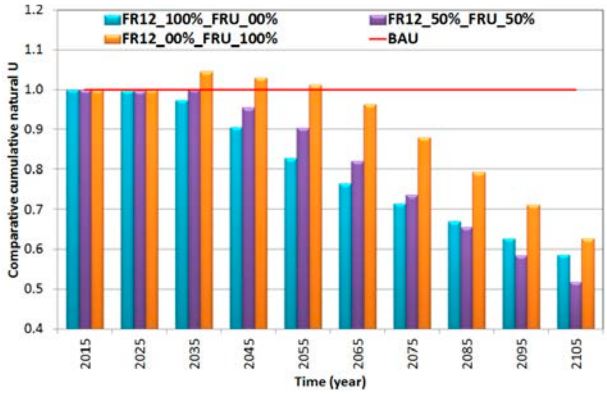


FIG. 3.178. Comparative cumulative natural uranium consumption.

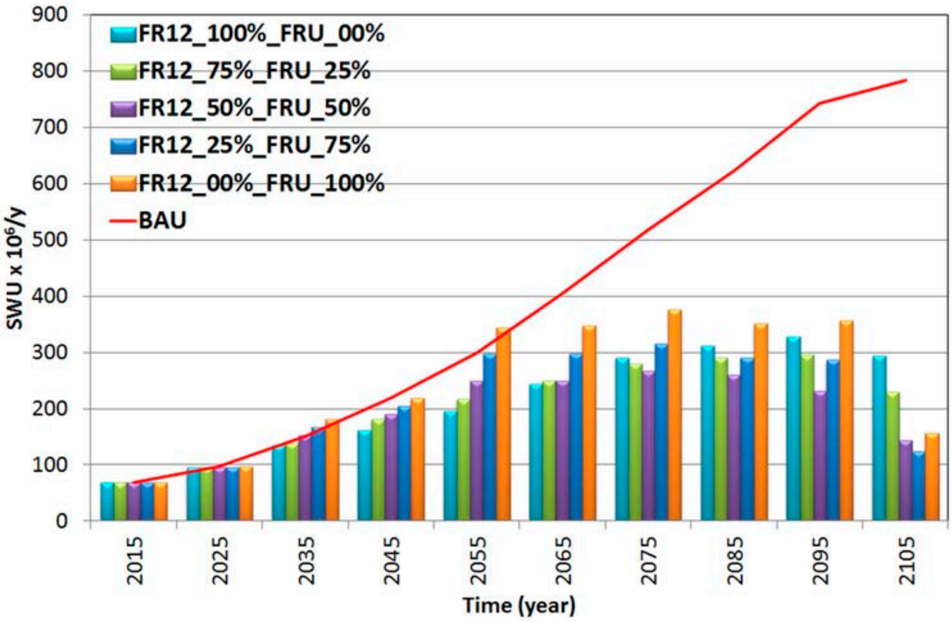


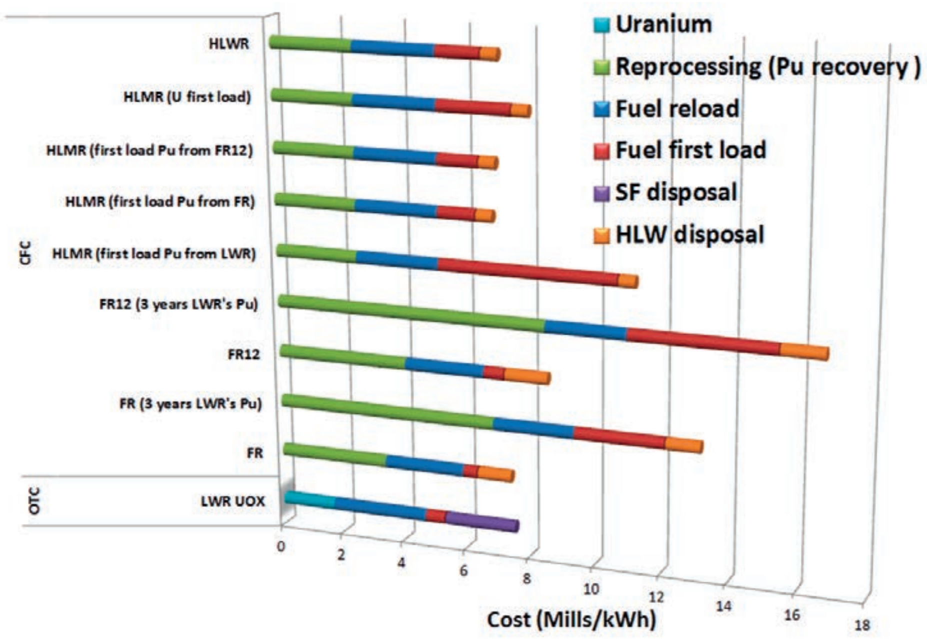
FIG. 3.179. Separative work unit requirements.

(b) Economic aspect of fast reactor deployment scenarios (^{235}U load versus uranium–plutonium load)

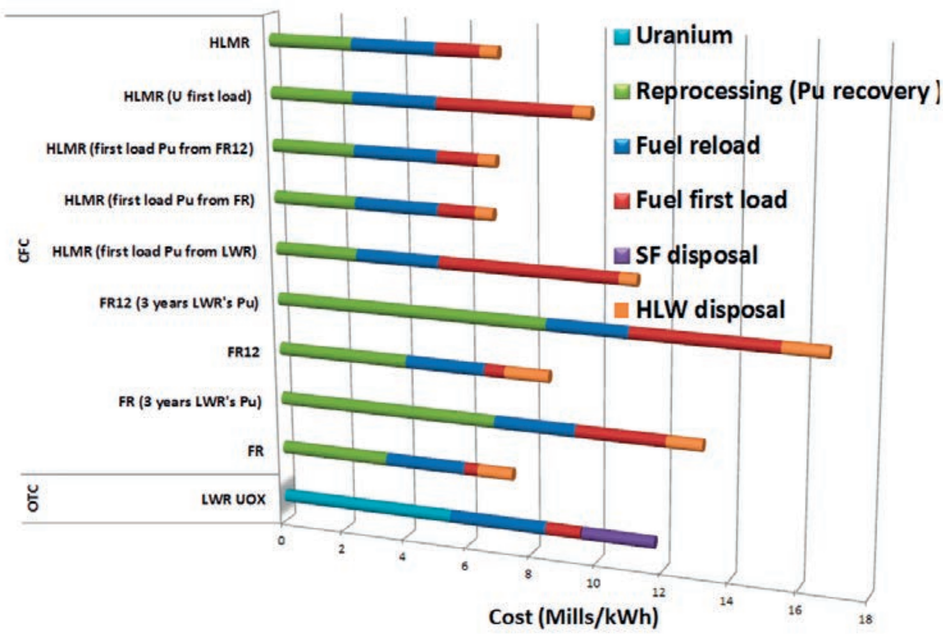
In this study, the focus is on the fuel cost while recognizing that the capital and operation and maintenance costs are significant components of the total LUEC. Fuel cycle cost analysis is based on a cost breakdown structure for a specific nuclear fuel cycle scheme, which includes fuel cycle components from uranium mining to HLW disposal.

Capital cost is influenced by a deep division of labor, a long production chain (from raw materials to final product) and R&D, so investment risk is significant. Fuel cost makes a much smaller contribution to the LUEC than the capital cost, which is a strong advantage for nuclear power over the fossil energy sources. Figure 3.180 shows the levelized fuel cycle unit cost associated with different reactors:

— LWR: a typical PWR design considered in the GAINS project.
— FR: a ‘break-even’ fast reactor considered in the GAINS project.
— FR12: a SFR with a breeding ratio of 1.2.
— HLMR: a heavy liquid metal cooled fast reactor with a breeding ratio of 1.05.



(a) Uranium = US $80/kg U.



(b) Uranium = US $260/kg U.

FIG. 3.180. Levelized fuel cycle cost.

The fuel cycle component encompasses uranium cost, reprocessing, fuel reload, first fuel load, spent fuel disposal and HLW disposal. Levelized fuel cycle cost of HLMRs using enriched uranium (natural uranium = US $80/kg U) for first loading is in the range between HLMRs using LWR plutonium for first loading and plutonium from fast reactors. It is comparable to levelized fuel cycle cost of LWRs operating in a once through fuel cycle. The levelized cost of HLMR with uranium startup is cheaper than that of the FR12.

The technology is economically viable under existing uranium cost. If the uranium cost increases up to US $260/kg, the uranium levelized fuel cycle cost of HLMRs using enriched uranium becomes lower than the levelized fuel cycle cost of LWRs operating in a once through fuel cycle. On the other hand, it approaches the fuel cycle cost of HLMRs using LWR plutonium. The latter option becomes more economic as the uranium cost increases. For a uranium cost of US $260/kg, the uranium levelized cost of HLMRs with uranium startup is still cheaper than the one of FR12 using LWRs plutonium for first loading and the first three years of refuelling, but becomes more expensive than FR12 using LWRs plutonium for the first loading.

These results indicate that fuel cost in the case of startup on enriched uranium will begin to rise. It may be economical to start from uranium first loading of HLMRs and then replace with first loading based on LWR/fast reactor plutonium.

(c) Alternative deployment strategy of fast reactor startup on enriched uranium fuel

This section considered the deployment strategy of the Russian designed BN-1200 SFR with startup on enriched uranium oxide fuel. In the current study, in the modelling scenarios of transition to sustainable NES with fast reactors on enriched uranium, a high case scenario was adopted of up to 5000 GW·h by 2100. There was a GAINS scenario modification with an enlarged rate of fast reactor commissioning from 2030 to 2050. The considered global scenario refers to an option where the capacities in NG1 are expected to have high growth (from 50% to 65%). The mathematical model consists of NG1 and half of the NG3 capacities (half of NG3 spent fuel). This means that the scenario works with thermal and fast reactors of NG1, as well as with the thermal reactors of NG3 (see Table 3.38). Spent fuel from NG3 is transported to common spent fuel storage of NG3 and is reprocessed immediately.

There are two scenarios of nuclear energy development by 2100 with different structure of reactor types: LWR with uranium fuel, FR-1200 with uranium fuel and FR-1200 with MOX fuel. The first scenario is based on joint operation of thermal reactors (ALWR-1000 — an advanced LWR) with UOX fuel and fast reactors (FR-1200 with MOX fuel). In the second scenario, commissioning of thermal units stops in 2030. Introduced reactors work until the end of lifetime. FR-1200 MOX and FR-1200 UOX units provide for replacement of missing capacities.

The electricity production of ALWR-1000 reactors (lifetime of 60 years) reaches 960 GW(e) by 2100 in Scenario 1. To provide the desired total demand (see Table 3.38), characteristics of the Russian designed BN-1200 SFR with MOX fuel in equilibrium conditions were used as an example of a typical fast reactor. The BN-1200 reactor (lifetime of 60 years) will be commissioned from 2021, with a summary electricity production running up to 2790 GW(e) by 2100.

Scenario 1 is not optimal due to the following inherent fundamental flaws:

- Long period of thermal reactors mass use entails accelerated depletion of cheap natural uranium.
- Full reprocessing of spent fuel with limited requirements of total fast reactors capacities leads to excessive plutonium stocks buildup. The refusal of irradiated nuclear spent fuel reprocessing would lead to the large amount of radioactive materials accumulation and will require construction of an ever increasing amount of spent nuclear fuel storage facilities.

Scenario 2 assumes that from 2030 all new installed capacity will be with fast reactors. In the case of insufficient amount of plutonium to launch the BN-1200 on MOX, uranium fuel can be used. In the case of BN-1200 on MOX, there would be savings of natural uranium, reducing plutonium stockpiles and the need for new

TABLE 3.38. CAPACITY OF NG1 AND 50% NG3 BY YEARS (GW(e))

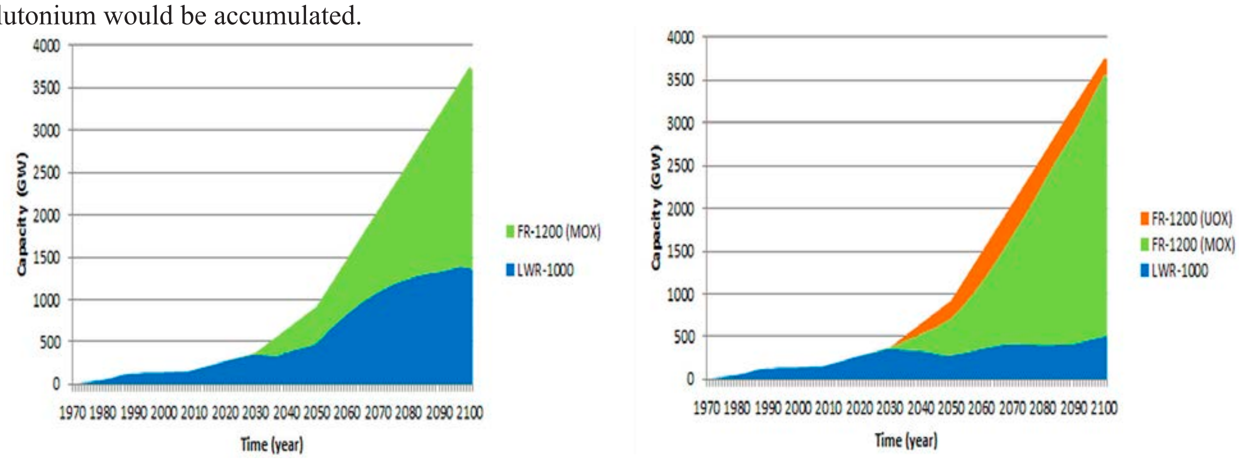
Year	NG1	50% NG3	Total
2008	149	0	149
2030	358	17	375
2050	853	68	921
2100	3250	500	3750

spent fuel storage facilities. There is a 10% operational plutonium supply in these scenarios; under such conditions, the accumulation of direct use material becomes problematic.

A chart of thermal and fast reactor capacities, depending on the time for Scenarios 1 and 2, is shown in Fig. 3.181. Figure 3.182 shows the annual natural uranium consumption in both considered scenarios. By 2100 in Scenario 1, the total natural uranium consumption is 11.189 million t, while the depleted uranium consumption is 1.09 million t. The annual demand for natural uranium is 46 500 t in 2020, 107 000 t in 2050 and 142 000 t in 2100 (the maximum is 177 000 t in 2076).

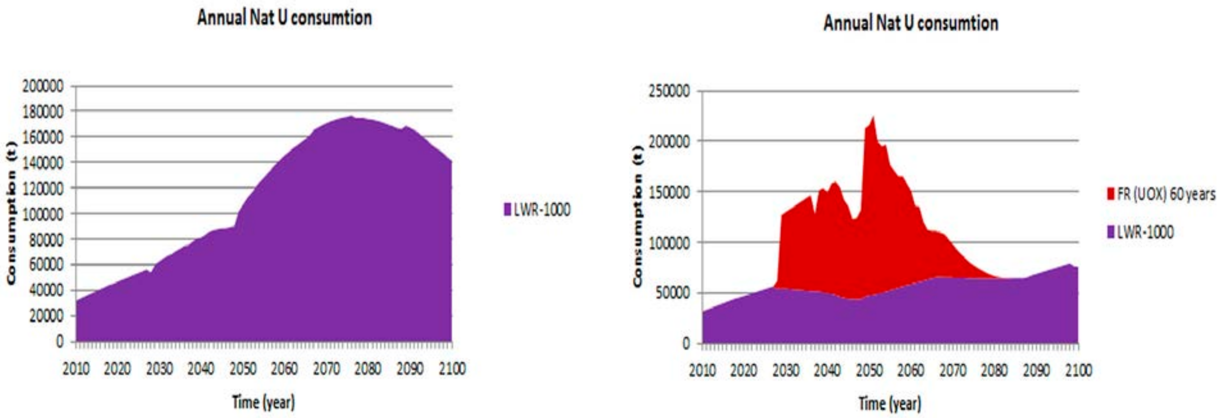
By 2100 in Scenario 2, the total natural uranium consumption is 9.91 million t, while the depleted uranium consumption is 1.59 million t. The annual demand for natural uranium is 46 500 t in 2020, 216 000 t in 2050 and 75 700 t in 2100 (the maximum is 226 000 t in 2051). Scenario 2 gives 11.4% savings of natural uranium, but leads to a 45.9% increase in the flow of depleted uranium. Figure 3.182 shows spurts in the annual natural uranium consumption for Scenario 2. The maximum consumption is 226 000 t/year in 2076 against 177 000 t/year in 2051 for Scenario 1, which is due to the FR-1200 (UOX) commissioning.

In both considered scenarios, there is a significant and growing mass of plutonium in storage at the end of the modelling period. By 2100 in Scenario 1, 929 t of plutonium would be accumulated, while in Scenario 2, 3846 t of plutonium would be accumulated.



(a) Scenario 1 (b) Scenario 2

FIG. 3.181. Total capacity of thermal and fast reactors.



(a) Scenario 1 (b) Scenario 2

FIG. 3.182. Annual natural uranium consumption.

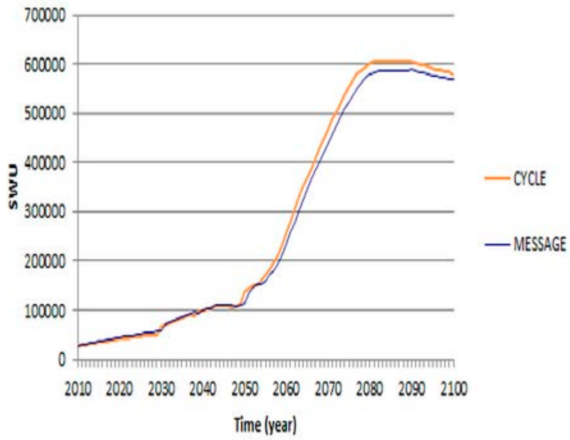


FIG. 3.183. Separative work unit demand, MESSAGE and CYCLE results comparison.

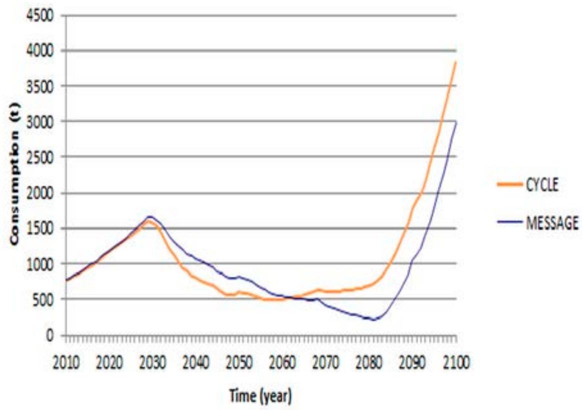


FIG. 3.184. Plutonium amount in storage, MESSAGE and CYCLE results comparison.

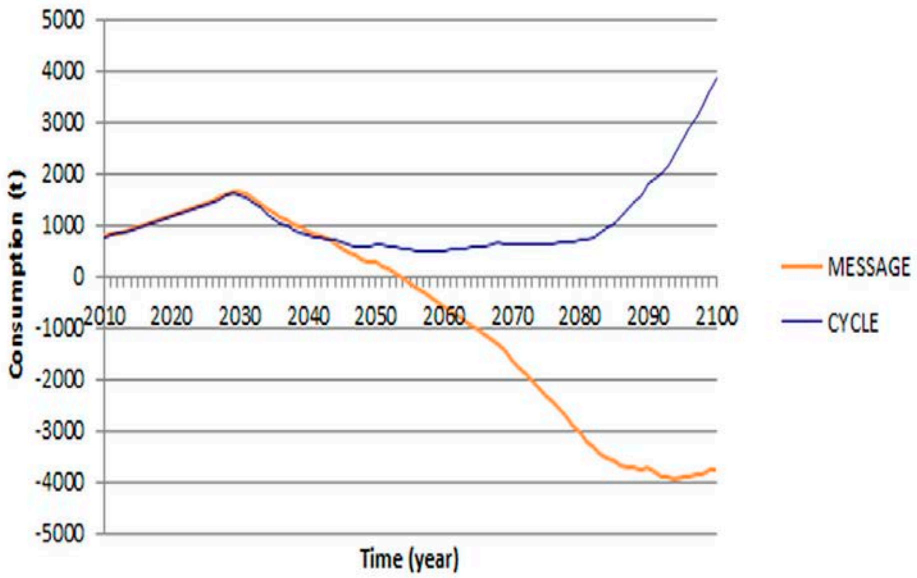


FIG. 3.185. Plutonium amount in storage. MESSAGE and CYCLE results comparison (without CYCLE average data).

(d) CYCLE and MESSAGE modelling results comparison

For global scenarios, which assume a high NG1 growth (50% to 65%) in nuclear energy, results were obtained with the MESSAGE and CYCLE software tools. The SWU demand, assessed with the two mentioned tools is quite consistent (see Fig. 3.183). From 2010 to 2050, graphic dependencies are similar; from 2051 to 2100 the differences in SWU show an average of 4.73%. Low data fluctuation (see Figs 3.184 and 3.185) was obtained through CYCLE output data, then averaged and used as input data for MESSAGE. The computation results of the two tools are considerably different in the absence of an averaged input data. The greatest difference can be seen in the parameter for the amount of plutonium in storage (see Fig. 3.185).

3.3.7.5. Conclusions

In summary, adding an FRU (uranium–plutonium–minor actinide nitride fuelled) that uses enriched uranium for startup and fast reactors FR12 using MOX fuel have advantages as well as disadvantages:

— The greater the share of FRU is added, the more likely a fleet of fast reactors can be deployed, since there are reasonable requirements for available plutonium that will limit the overall fast reactor growth rate. The fleet of fast reactors in the FR12_00%/FRU_100% case could be increased by 150% as compared to the FR12_100%/FRU_00% case by the end of century.
— In the short and medium terms, FRU introduction allows the deployment of the high scenario fast reactor programme under LWR reprocessing capacity limitations.
— By 2100, all options with fast reactors have comparable natural uranium savings in comparison with the BAU case.
— Using enriched uranium for first fuel loading of fast reactor requires additional enrichment capacity but reduces the reprocessing capacity requirements.
— Options for fast reactor introduction with a FRU share up to 50% and a closed nuclear fuel cycle show positive effects on spent fuel accumulation. Spent fuel accumulations for FRU share options of 0%, 25% and 50% drop to zero level in 2065, 2080 and 2090, respectively. Similar results are obtained for plutonium and minor actinide inventories in long term storage facilities for LWR spent fuel.

Deployment strategies with fast reactors that are launched with enriched uranium fuel (i.e. alternative deployment strategies to fast reactors launched with MOX fuel produced from reprocessed spent fuel of thermal reactors) also have clear advantages and disadvantages:

— Savings of natural uranium a about 11% after the 80 year period of modelling.
— There is strong demand for SWU facilities from 2030 to 2070, with sharp irregular shaped peaks in 2044 and 2052. There is some concern associated with downtime of enrichment facilities after 2070.
— From 2080 to 2100, there is a dramatic accumulation of plutonium in storage facilities, from 500 t to 3800 t. An amount of 400 t of plutonium is a minimal operational reserve.

There are very few scenarios based on fast reactor startup with enriched uranium. This is a test scenario that requires further development and improvement.

3.3.8. Sustainable regional scenario with 'adiabatic' lead fast reactors in selected countries

3.3.8.1. Introduction

This scenario study aimed to identify sustainability benefits (economic and environmental) for all the subjects involved in a 'win-win' strategy, and was part of the INPRO collaborative project SYNERGIES, under Task 1, on evaluation of synergistic collaborative scenarios of fuel cycle infrastructure development. The complete case study can be found in Annex IX on the CD-ROM accompanying this publication. Some intermediate results of the study were presented at the ICONE22 conference in 2014 and are included in its proceedings [3.85], which are referenced in this section.

3.3.8.2. Objective and problem formulation

Reflecting upon the current situation in Europe, where on one side, a number of countries have adopted decisions on cutting down nuclear or on its total phase out and, on the other side, conditions for new nuclear deployment remain objectively favorable because of greenhouse gas emission constraints and well established common electrical grids of high capacity, the study addressed a hypothetical scenario involving a country with a nuclear moratorium that nevertheless maintains R&D of Generation IV reactors and has a utility that operates some thermal spectrum power reactors abroad, and several countries in the region with favorable stance towards nuclear that are potentially interested in embarking upon or expanding their national nuclear energy programmes [3.85, 3.86].

The point of the study was that for such region a multinational approach to operation could be considered involving the supplies of electricity from nuclear power plants with evolutionary and innovative reactors built and operated abroad, as well as shared nuclear fuel cycle facilities.

The study focused on analysing the benefits from operating at a multinational level with the deployment of a fleet of PWRs and subsequently, at a proper time, LFRs [3.85]. Specifically for innovative LFRs, a closed fuel cycle was considered where at each refuelling, the reactor is fed by only natural uranium based fuel and gets rid of only fission products as a discharge. Such reactor/fuel cycles are hereafter called 'adiabatic'. Owing to introduction of such reactors, a substantial reduction in uranium consumption and final disposal requirements can be achieved. A demonstrator of this type of reactor, a Generation IV liquid lead cooled nuclear fast reactor, is proposed to be constructed in Mioveni (Romania) by the Falcon Consortium, integrating so far several industrial and research partners from the Czech Republic, Italy and Romania.

As a nuclear moratorium bearing country looking for deployment and operation of nuclear power plants abroad, Italy was considered as region III, while the countries potentially seeking for the introduction or expansion of the nuclear were region I and included Albania, Bulgaria, Romania and all the countries of the former Yugoslavia (except Slovenia); region II included the Czech Republic, Hungary, Slovakia and Slovenia; and region IV Ukraine. The dynamic modelling of nuclear energy evolution scenarios was performed for the period of 100 years in the timeframe 2020–2120 [3.85].

(a) Projections for electricity generation

Projections for electricity generation in the countries considered were derived from relevant projections of GDP growth available at the time of the study and suggested the following per annum growth rates [3.85]: 1% for countries from regions II and III; and 3.3% prior to 2050 and 1% after for countries from regions I and IV.

3.3.8.3. Assumptions, methods, codes and input data used

In order to simulate the nuclear scenario in the four regions, it was necessary to set the contribution from nuclear power plants to the generation of electricity. These contributions were set as follows [3.85]:

— 16%, 11%, 0%, 62% at the scenario startup time for countries of regions I, II, III and IV, respectively, with a note that at the time of the study, Italy (region III) imported 10% of electricity from nuclear power plants operating abroad.
— 25%, 36%, 25% and 40% for the respective regions in 2120.

Other important assumptions of the study were as follows [3.85]:

— In the scenarios, all types of the currently operated thermal spectrum nuclear reactor were represented by a generic PWR.
— The innovative LFRs were assumed to be ready for deployment starting from 2040.
— The LFR was assumed to possess the 'adiabatic' characteristics described above [3.87, 3.88].

The main assumptions adopted to perform the simulations were the following:

— The scenario with synergies was characterized by the sharing of all the fuel cycle facilities by all the regions, oppositely to the non-synergetic case implying that each region manages its own fuel cycle independently from the others. In both cases, the second region will satisfy its needs only with PWRs. That implies that in the second scenario, plutonium from this region will not be available to start LFRs in the other regions.
— Until 2040, all the nuclear fleets will be based only on PWRs operating with UOX fuel, after that year, depending on the availability of plutonium, the new power needs will be covered as much as possible by LFRs operation, the remaining uncovered fraction of power being assured by PWR operation.
— The existing nuclear power plants in 2020 will reach their end of life between the 2030 and 2035.
— The computation of the plutonium balance takes account of the plutonium available in 2020 in the storage facilities and cooling pools (produced in each region before 2020).

— The nuclear power plants could be installed in a ‘continuous way’, so it is not accounted the granularity of the plants. For example, if in a year it is necessary to have 200 MW in a given region, such a power amount is installed; in a more realistic simulation, the power should increase only as a multiple of the reactor values, 600 MW or 1 GW depending on the type.

A MATLAB program that simulates the evolution of the installed nuclear power and computes the material balances and economic expenditures was developed. The mix between both types of reactor was determined in function of the required nuclear electricity and transuranic availability; all the main parameters listed in the corresponding annex were accounted in the calculations according to the above assumptions. The fuel cycle was modelled by a matrix that contains the fuel isotope composition at the beginning and at the end of life of both types of reactor.

3.3.8.4. Summary presentation and analysis of the results

Table 3.39 shows the values of the electricity consumption for each region based on the above assumptions.

Applying to these values of electricity consumption totals, the percentages for the contribution of nuclear power plants in each region resulted in the data shown in Fig. 3.186. These values were used as input to calculate the material flows and expenditures in both simulations (with synergies and without). As previously mentioned,

TABLE 3.39. EVOLUTION OF THE ELECTRICITY CONSUMPTION IN EACH REGION, 2020–2120 (TW·H)

	Region				
	I	II	III	IV	Total
2020	162	135	314	138	749
2050	429	182	423	366	1400
2100	706	299	696	601	2302
2120	706	299	696	601	2302

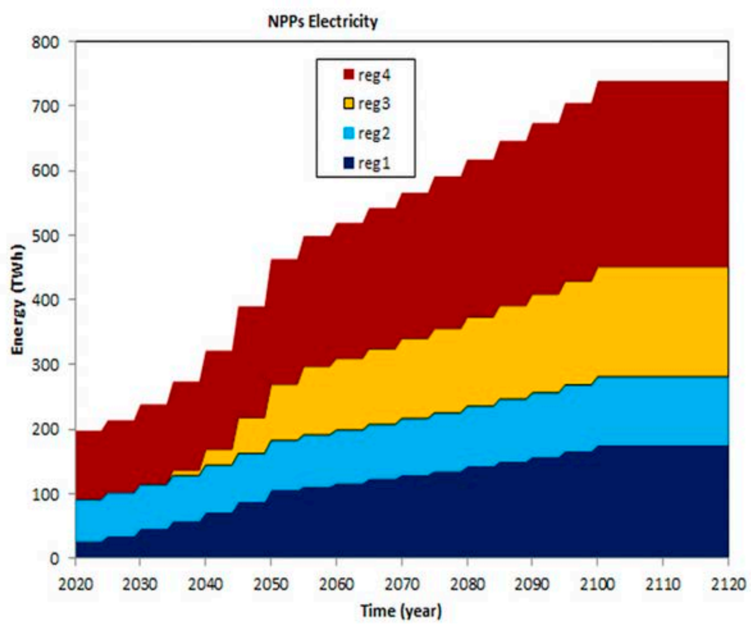
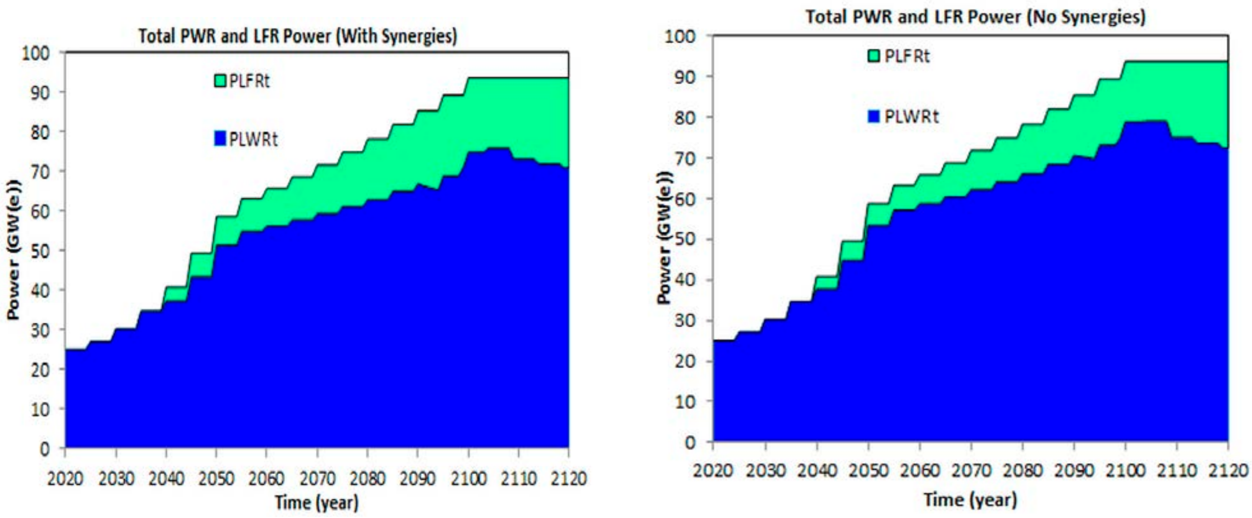


FIG. 3.186. Evolution of electricity consumption generated by nuclear power plants for each region.



(a) Regions collaborate (b) Without collaboration

FIG. 3.187. Total installed electrical power capacity from the PWR and LFR fleets (regions I–IV).

after 2040 the installation of LFRs was assumed, depending on the available plutonium; Fig. 3.187 shows the resulting contributions of both types of reactor to the total installed nuclear power in the two scenarios analysed.

(a) Material balances

The effects on the fuel costs of different strategies of collaboration between regions that embrace the production of electricity with nuclear power plants were analysed. In this, the important factors of the economy of scale for the front end and back end fuel cycle facilities were taken into account (based on data from Appendix II). Figures 3.188 and 3.189 present the results of the performed material balance calculations for the dynamic NES evolution scenarios, juxtaposing the variants with no collaboration in nuclear fuel cycle to those with synergistic (shared) front end (enrichment) and back end (reprocessing) fuel cycle arrangements.

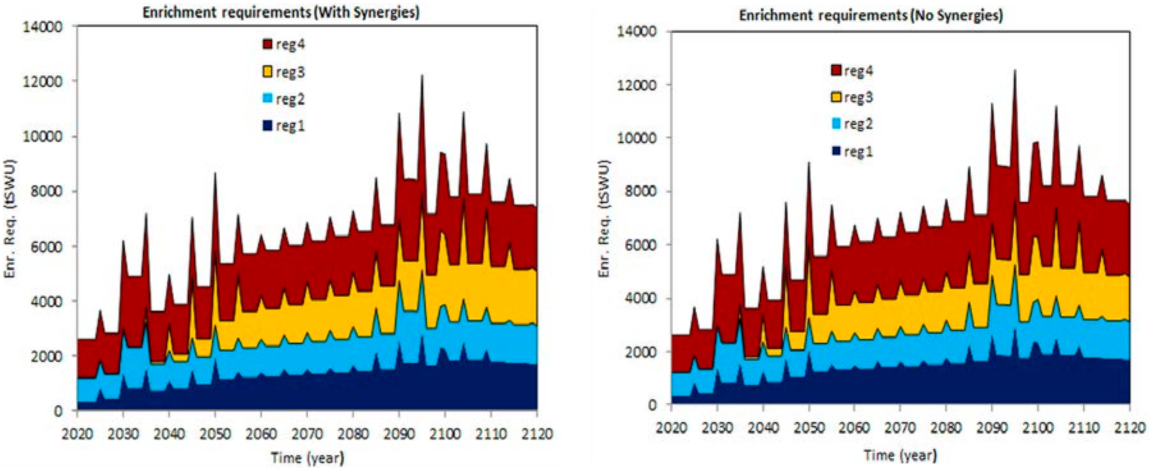
From the point of view of material balances, the factor determining the differences in the results between the two scenarios is given by managing the plutonium stocks. In the non-synergic case, the plutonium from the second region remains unused in the deposit because this region does not install LFRs; in the synergetic case, this plutonium is used by the others regions to start an extra number of LFRs. The amount of plutonium from the second region is a small fraction from the total one; consequently, there are not remarkable differences in the material balances between both considered scenarios.

Long lived, highly radiotoxic isotopes of heavy metals are of highest concern in final disposal of HLW — the generic goal being to minimize them. To reflect how the considered synergistic and non-synergistic fuel cycle options could address this issue, Fig. 3.190 presents the inventories of plutonium in reactors, storages and cooling pools for the cases considered.

It is worthwhile to point out that if no LFRs were used to answer the nuclear electricity needs settled in these scenarios, the total cumulated natural uranium consumption would be 1.44 million t, meaning an increase of 19% with respect to the scenario where this type of reactor is introduced in a synergetic way. Once again, without LFRs the total amount of plutonium produced by the PWRs would be 1515 t, with an increase of 15% with respect to the synergistic case.

(b) Economic figures

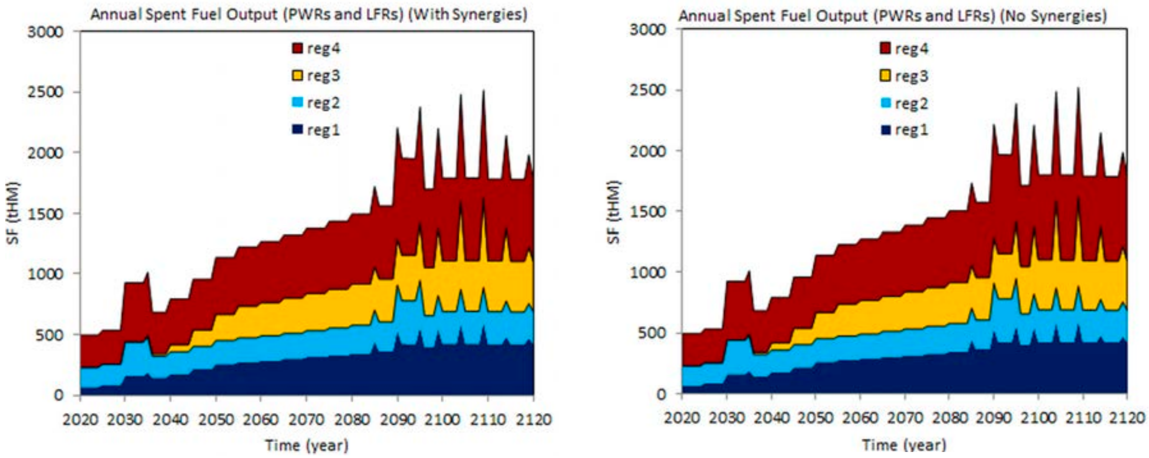
The economic analysis was based on data presented in Appendix II. The calculations were performed at a discount rate of 5% [3.85]. The important assumption was also that reprocessing and enrichment plants increase their capacity to answer the fuel requirements following a ten year period. This means that the fuel enrichment and spent fuel output in an interval of ten years were averaged along the full period of modelling, then with these values where determined the levelized costs for each interval employing the data from Appendix II, as is shown in



(a) Regions collaborate

(b) Region manages the fuel cycle independently

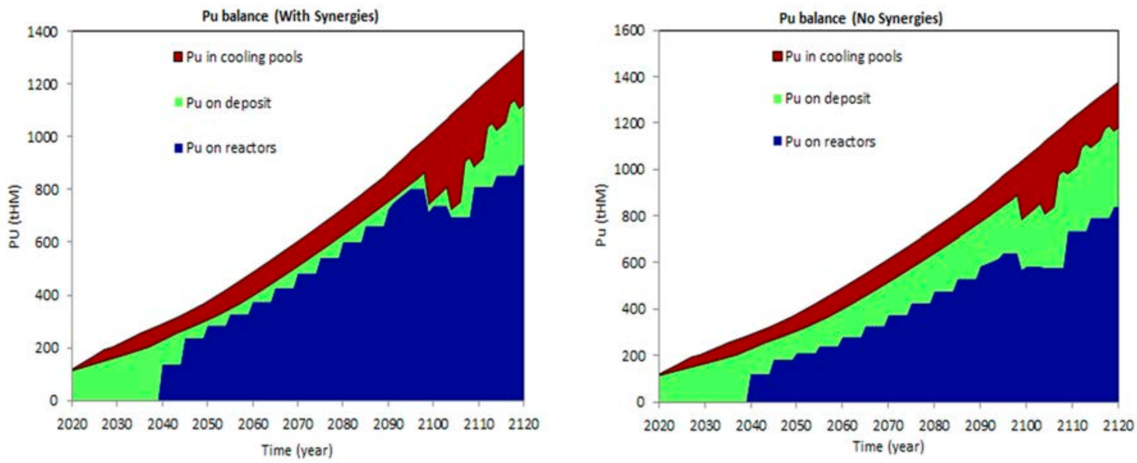
FIG. 3.188. Uranium enrichment requirements for each region.



(a) Synergistic case

(b) Non-synergistic case

FIG. 3.189. Annual spent fuel output for each region.



(a) Synergistic case

(b) Non-synergistic case

FIG. 3.190. Cumulative plutonium in reactors, at reprocessing plants and in cooling fuel storage.

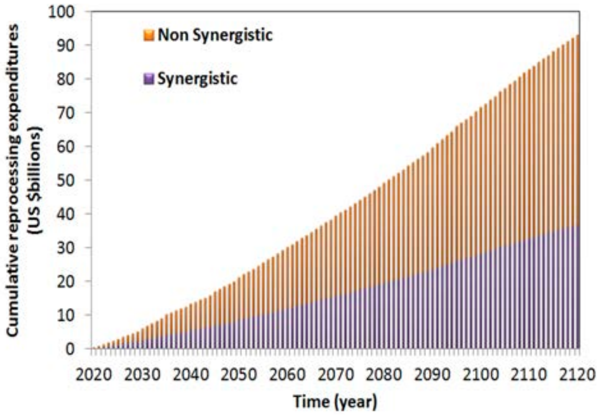


FIG. 3.191. Cumulative enrichment expenditures for separate and synergistic cases.

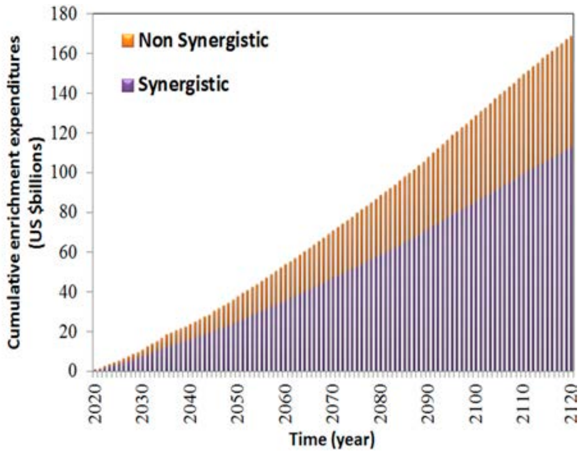


FIG. 3.192. Cumulative reprocessing expenditures for separate and synergistic cases.

TABLE 3.40. MATERIAL BALANCES AND EXPENDITURES FOR CONSIDERED SCENARIOS

	Non-synergistic	Synergistic	Differences	
Natural U consumption (t HM)	1.25×10^6	1.21×10^6	4.0×10^4	3%
Depleted U consumption (t HM)	1.66×10^4	2.00×10^4	-3.4×10^3	−21%
Pu total (t HM)	1330	1291	39	3%
Enrichment expenses (US $)	6.11×10^{10}	4.02×10^{10}	2.09×10^{10}	34%
Reprocessing expenses (US $)	11.9×10^{10}	6.11×10^{10}	5.79×10^{10}	49%

Annex IX. Figures 3.191 and 3.192 show the time dependencies for cumulative expenditures related to front end and back end fuel cycle services (i.e. enrichment and reprocessing).

The calculations performed assumed uniform deployment of nuclear power plants across all considered regions. Should it not be the case, then transmission costs for imported/exported electricity would need to be added. It was noted that high voltage, direct current lines offering reduced losses in transmission [3.89] and could be considered in such analysis, but their construction costs and availability at different times in the simulation period would need to be carefully evaluated, also taking into account that they will transmit all electricity and not only nuclear electricity [3.85]. The most relevant differences between both scenarios are summarized in Table 3.40.

Comparing the results for both scenarios, it can be observed that power distribution among the two types of reactor and the mass balances present the same time evolution behaviour, with little quantitative differences. The numeric deviations are mainly determined by the restriction that the second region does not install LFRs, in the non-synergic scenario the plutonium from this region remaining in deposit, in contrast to the synergetic scenario, where this amount of plutonium is added to the ‘common pool’.

The studies performed concluded that sharing of the front and back end fuel cycle facilities could help effectively to cut down costs and the overall expenditures by 34% for the enrichment (front end) and by 49% for the reprocessing (back end). The overall absolute value savings in these cases would be US $20.9 billion and US $58 billion, respectively [3.85]. A positive role of the LFR started up and operated on mixed uranium–plutonium fuel in cutting down the out of pile inventories of heavy metals was noted. The considered scenarios were found, however, to be inadequate for the purpose of HLW minimization in nuclear phase outs, where dedicated facilities for transuranic incineration would be needed.

3.3.8.5. Conclusions

This study addressed a scenario of nuclear energy development in several regions of Europe under the different stances of different countries towards nuclear energy. To address this diversity, the options analysed included deploying and operating nuclear power plants abroad and just importing nuclear generated electricity and options to share the infrastructures for fuel enrichment and reprocessing including those needed for introduction and operation of innovative LFRs. An electricity import option was shown to be potentially viable, with HVDC grids offering relatively low transmission costs. Sharing the front and back end fuel cycle facilities demonstrated potential reductions in fuel cost in the range of 35–50%. Further studies could address in more detail the transmission costs and take into account non-uniform deployment patterns for nuclear power plants with evolutionary and innovative reactors across different countries.

3.3.9. Long term scenario study for nuclear fuel cycle in Japan

3.3.9.1. Introduction

After the accident at the Fukushima Daiichi nuclear power plant, caused by the Great East Japan Earthquake, on 11 March 2011, the Energy and Environment Council, comprised of cabinet members in Japan, directed the Japan Atomic Energy Commission (JAEC) to evaluate options for the future of the nuclear fuel cycle. The scenario evaluations were carried out in 2012 considering various shares of nuclear energy supply until 2030. Although the Council proposed a complete phase out of nuclear power by the 2030s, the new government which formed in December 2012 decided to reconsider Japanese energy policy from scratch, including the phase out proposal. On 11 April 2014, a new strategic energy plan was announced, setting a policy framework for the next 20 years. Under this plan, the degree of dependency on nuclear energy is to be reduced as much as possible to a target volume of nuclear generated electricity that takes Japan's energy constraints into consideration. Nuclear power will continue to be one of the key 'base load electricity sources' contributing to the stability of energy supply and the closed nuclear fuel cycle policy will be promoted. Moreover, it calls for the promotion of fast reactor R&D and utilization of the prototype fast breeder reactor Monju as an international centre for R&D, oriented to decrease the mass and hazards of radioactive waste and to improve the technology for non-proliferation.

The INPRO SYNERGIES project objectives include discussion and consultation about several specific collaborative scenarios and details of collaborative architectures on a pathway towards long term sustainability. Given the situation of energy policy in Japan, this study focuses on various fuel cycle options, including scenarios for collaborative transition from LWRs to fast reactor based fuel cycles, and identifies the characteristics of each option in the view of long term sustainability in Japan. This section presents a revised study originally presented to a subcommittee of the JAEC [3.90] and at the FR13 conference [3.91]. The complete case study can be found in Annex XI on the CD-ROM accompanying this publication.

3.3.9.2. Objective and problem formulation

An evaluation was conducted in order to investigate several key indicators such as nuclear capacity, natural uranium demand, plutonium stockpile and inventory, spent fuel stockpile, and radioactive waste generation and disposal, based on the long term use of nuclear energy and the transition from LWRs to fast reactors with reprocessing of spent fuel in Japan. Three nuclear scenarios were selected as the target in the evaluation until around 2150, when the impact of the transition from LWRs to fast reactors would be most visible:

— Full reprocessing (fast reactor deployment): All spent fuel is reprocessed, and fast reactors are deployed for the replacement of LWRs after 2050.
— Partial reprocessing (Rokkasho Reprocessing Plant): Spent fuel exceeding the capacity of the Rokkasho Plant and all spent fuel generated after its closure is directly disposed of after being stored in interim storage facilities.
— Full direct disposal: All spent fuel is directly disposed of.

Moreover, four nuclear power capacity cases were assumed for the scenarios above in accordance with the energy policy debate in Japan by the long term planning subcommittee of the JAEC after the accident at the Fukushima Daiichi nuclear power plant (see Table 3.41 and Fig. 3.193):

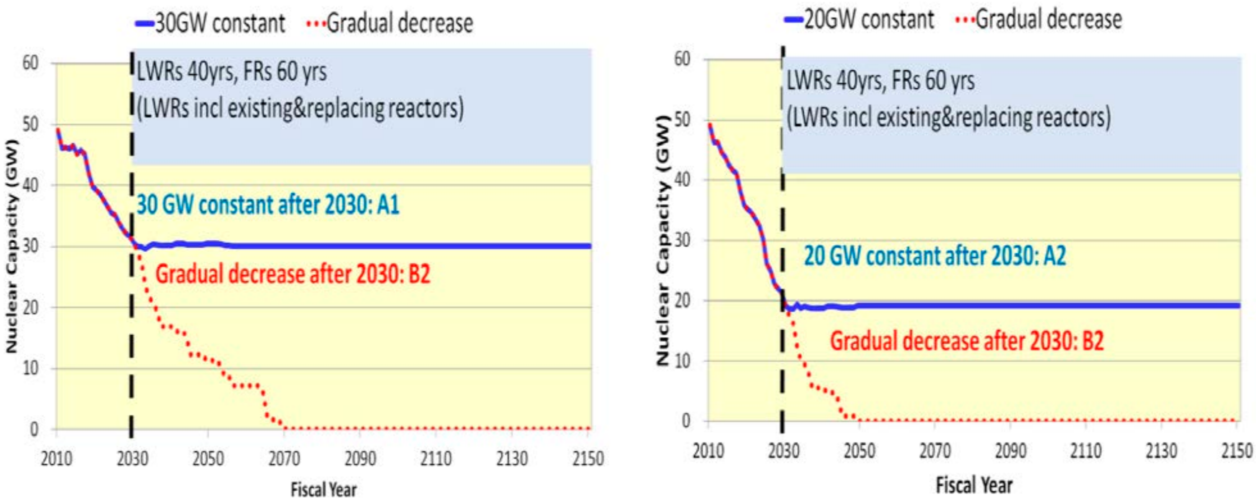
— Case A1: 30 GW(e) in 2030, remaining constant after 2030.
— Case A2: 20 GW(e) in 2030, remaining constant after 2030.
— Case B1: 30 GW(e) in 2030, gradual decreasing to zero after 2030.
— Case B2: 20 GW(e) in 2030, gradual decreasing to zero after 2030.

3.3.9.3. Assumptions, methods, codes and input data used

This study uses a cross-cutting characteristic evaluation tool developed by the Japan Atomic Energy Agency to treat the whole NFC supply chain. The major assumptions for the long term scenario evaluations are provided in Table 3.42. These assumptions were made based on the short term scenario evaluations until 2030, conducted by the Technical Subcommittee on Nuclear Power, established by the JAEC. The assumptions of facilities were applied adequately in each case as necessary (e.g. assumptions for reprocessing plant availability were considered in the recycling case only).

TABLE 3.41. EVALUATION CASES

Case	Nuclear capacity	Full reprocessing (fast reactor deployment)	Partial reprocessing (Rokkasho Plant)	Full direct disposal
A1	30 GW(e) constant	X	X	X
A2	20 GW(e) constant	X	–	X
B1	Gradual decrease from 30 GW(e)	X	X	X
B2	Gradual decrease from 20 GW(e)	X	–	X



(a) 30 GW in 2030 (b) 20 GW in 2030

FIG. 3.193. Long term nuclear energy scenarios for nuclear capacity.

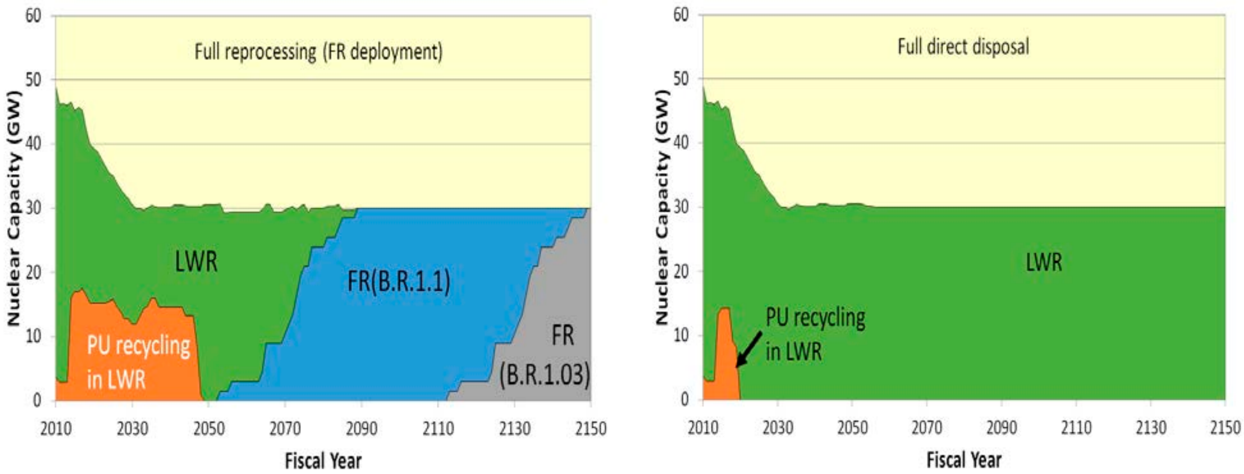
TABLE 3.42. MAJOR ASSUMPTIONS

	Item	Condition
Fast reactor	Introduction timing	Demo. reactor: 2025 Comm. reactor: 2050
	Av. burnup	60–150 GW·d/t
	Breeding ratio	1.03–1.1 (Burner reactor ~0.5)
	Capacity per unit	Demo. breeder reactor: 750 MW(e) Comm. reactor:1500 MW(e)
	Lifetime/load factor	60 years/~80%
LWR	Av. burnup	BWR: 45 GW·d/t PWR: 49 GW·d/t Reactors past: 30–40 GW·d/t Pu recycling: under 45 GW·d/t After 2030 all reactors: 60 GW·d/t
	Capacity per unit	Past: actual record Future reactors: 1200 MW(e)
	Lifetime/load factor	Existing reactors: 40 years/Until 2011: actual record, After 2012: 80%
	Pu recycling	According to Pu utilization plan including Pu recovered at overseas installations
LWR reprocessing facility	Rokkasho Plant	Operation until 2052 2012: 80 t U 2013: 320 t U 2014: 480 t U 2015: 640 t U After 2015: 800 t U
	SNF storage facility	Capacity: 3000 t HM (Rokkasho Plant)
	After Rokkasho Plant	Possible reprocessing of MOX fuel and high burnup fuel No recycle for recovered U MA recovering is considered Fuel of BWR and PWR is mixed and reprocessed within the capacity
	Vitrification facility	Production conditions for vitrification: 1.25 cask/t
Fast reactor reprocessing facility	Commercial facility	Starts operation after the fast reactor deployment, 100 t/year or 200 t/year MA recovery considered (breeder reactor) Transuranic elements are vitrified (burner reactor)
	Vitrification facility	Production conditions for vitrified waste: fission products oxide 10%, 2.3 kW/cask
Storage facility	Interim storage facility (Mutsu RFS)	Starts operation: 2013 Storage term: within 50 years Max. capacity: 5000 t Annual storage: 200–300 t/year
	SNF storage facility	Recycling: storage period of less than 40 years Direct disposal: storage period of 48 years (to be increased on demand)
	HLW storage and management facility	Storage period: 50 years, constructed according to the plan in the near term Capacity to be increased on demand
Geological repository	Vitrified waste	Starts operation in around 2037: upright position in hard rock
	SNF direct disposal	Starts operation in around 2047: upright position in hard rock

TABLE 3.42. MAJOR ASSUMPTIONS (cont.)

Item		Condition
Others	Ex-core time	LWR cycle: 4 years or more Fast reactor cycle: 5 years or more
	Fuel cycle losses	Fuel fabrication: 0.1% Reprocessing: ~0.5% (LWR), ~0.8% (fast reactor)

Note: BWR — boiling water reactor; HLW — high level waste; LWR — light water reactor; MA — minor actinides; MOX — mixed oxide; PWR — pressurized water reactor; SNF — spent nuclear fuel.



(a) Full reprocessing

(b) Full direct disposal

FIG. 3.194. Nuclear capacity of case A1, 30 GW(e) constant after 2030.

3.3.9.4. Summary presentation and analysis of the results

The main findings of the full reprocessing scenario and the full direct disposal scenario in the 30 GW(e) constant after 2030 case A1 are presented here. Other results are described in Annex XI. Nuclear capacities of A1 are shown in Fig. 3.194. In the full reprocessing scenario, all LWRs were replaced with fast reactors in about 35 years after 2053 considering the timing of the decommissioning of LWRs using plutonium recovered from LWR and fast reactor reprocessing plants. On the other hand, in the direct disposal scenario, plutonium recycling in LWRs with up to 14 GW in total was conducted for ten years using plutonium recovered from overseas facilities.

Cumulative natural uranium demands are shown in Fig. 3.195. The full reprocessing strategy made it possible to reduce natural uranium demand drastically after the fast reactor deployment and to be fully independent from foreign natural uranium resources around 2090. Figure 3.196 provides spent fuel stockpiles. The spent fuel stockpile reached up to 40 000 t before 2050 and became constant at about 25 000 t after 2080 in the direct disposal scenario; additional storage capacity of 10 000 t to 20 000 t was required.

Radioactive waste volumes for geological disposal, HLW and LLW are shown in Fig. 3.197. With regard to the full reprocessing scenario, LLW volume increased due to the deployment of reprocessing facilities, whereas vitrified waste volume decreased. As a result, the total volume of radioactive wastes for geological disposal was reduced to less than half of that of the full direct disposal scenario.

Minor actinide inventories are shown in Fig. 3.198. In the full reprocessing scenario, the minor actinide inventory in the whole fuel cycle was kept low by conducting the plutonium and minor actinide recycling in fast reactors. Before the start of the repository for vitrified waste in 2037, most minor actinide inventories were included in vitrified wastes generated at the Rokkasho Plant, where no minor actinides were recovered and in interim storage facilities. After the start of the repository, vitrified wastes were disposed of underground while

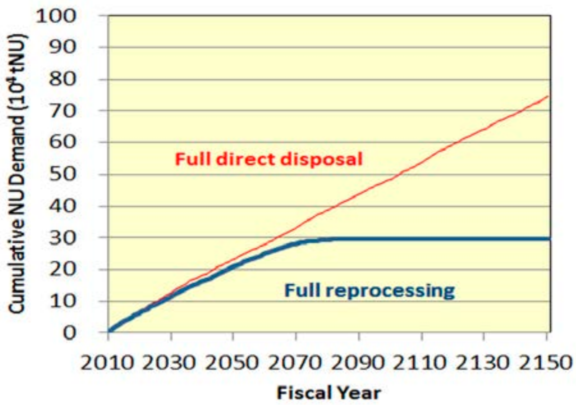


FIG. 3.195. Cumulative natural uranium demand of case A1, 30 GW(e) constant after 2030.

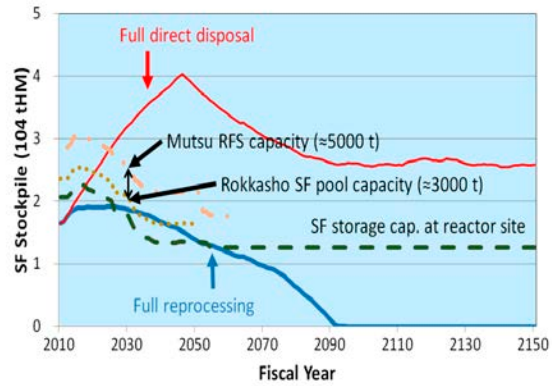
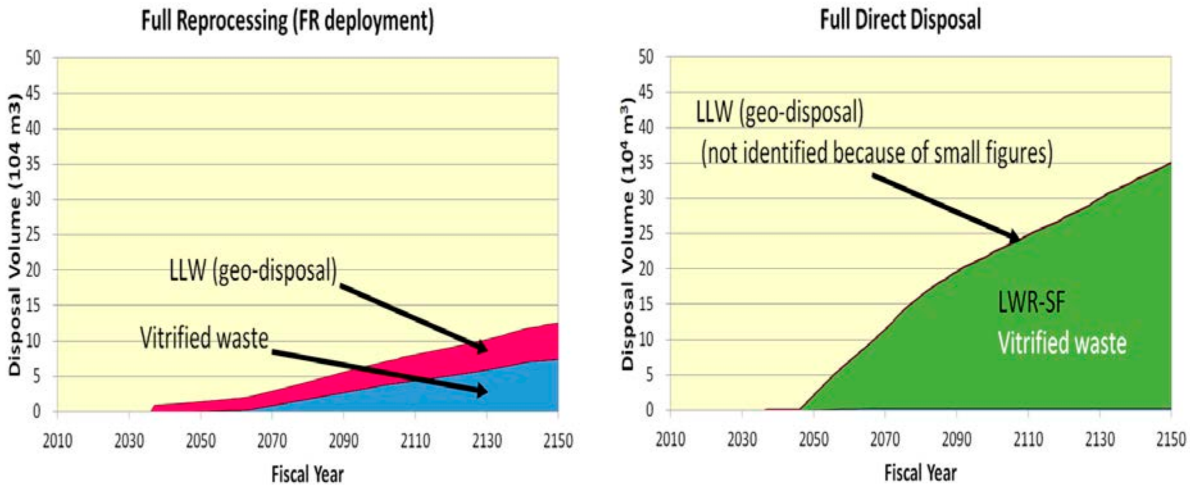


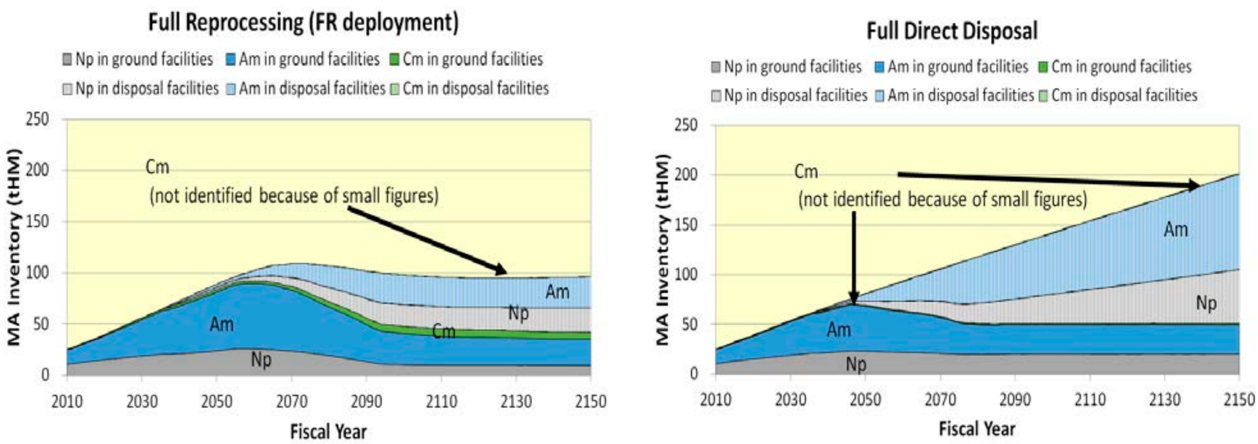
FIG. 3.196. Spent nuclear fuel stockpile of case A1, 30 GW(e) constant after 2030.



(a) Full reprocessing (b) Full direct disposal

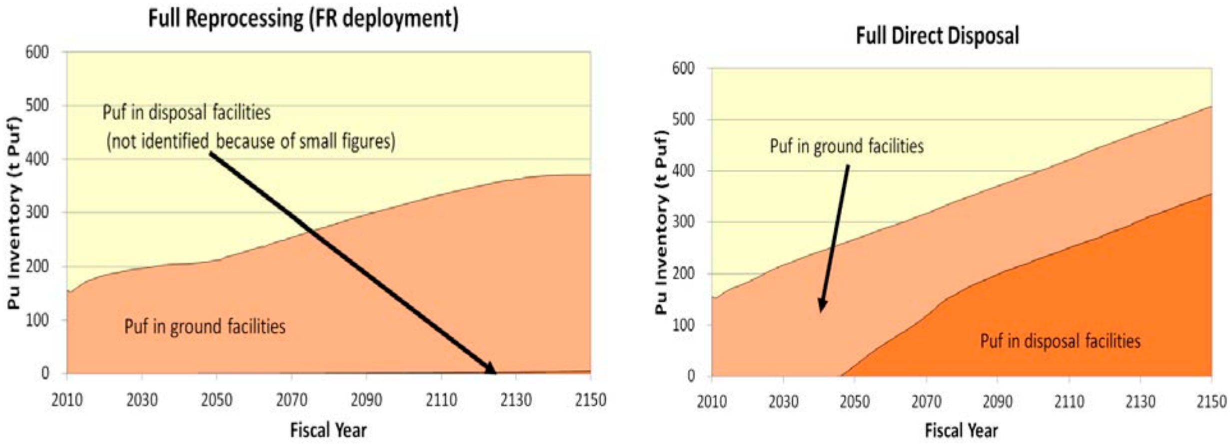
Note: Volume of vitrified waste, LLW (geodisposal) and spent fuel at the time of disposal.

FIG. 3.197. Disposal volume of high level waste and low level waste (geological disposal), 30 GW(e) constant after 2030.



(a) Full reprocessing (b) Full direct disposal

FIG. 3.198. Minor actinide inventory in the nuclear fuel cycle of case A1, 30 GW(e) constant after 2030.



(a) Full reprocessing (b) Full direct disposal

FIG. 3.199. Plutonium inventory in the nuclear fuel cycle of case A1, 30 GW(e) constant after 2030.

the amount of storage facilities were reduced; as reprocessing for fast reactor deployment starts in 2050, the main inventory is sifted to the minor actinides in fuels at reactors.

Figure 3.199 shows plutonium inventories. In the full reprocessing scenario, the full reprocessing strategy enables a lower plutonium inventory in the whole fuel cycle by the fast reactor deployment following the implementation of plutonium recycling in LWRs.

3.3.9.5. Conclusions

The presented evaluation was conducted to investigate several key indicators (e.g. nuclear capacity, natural uranium demand, plutonium stockpile and inventory, spent fuel stockpile, radioactive waste generation and disposal based on the long term use of nuclear energy) as they apply to a transition from LWRs to fast reactors with reprocessing of spent fuel in Japan. Results indicate that the full reprocessing strategy has a potential to reduce natural uranium demand, SNF stockpile, radioactive waste and plutonium inventory compared with direct disposal strategy (and the partial reprocessing, see Annex XI) in all cases of nuclear capacity: constant after 2030 and gradual decrease to zero after 2030 (including cases A2 and B2, see Annex XI). Especially in the cases of the constant decrease after 2030, the reduction effects were significant. In the light of international long term prospects, the full reprocessing strategy can reduce radioactive waste and plutonium inventory worldwide through international cooperation.

3.3.10. Modelling of regional collaborative deployment scenarios aimed at solving the problem of accumulating spent nuclear fuel inventory

3.3.10.1. Introduction

Deployment of nuclear power will likely be accompanied by the growth of global and regional nuclear fuel cycle services markets and enhancing of the multinational and multilateral cooperation. A mature market already exists for the fuel cycle front end, which enables the start or expansion of a national nuclear power programme without development and construction of front end elements of the nuclear energy infrastructure. nuclear fuel cycle services can be provided from technology holder countries or from international fuel cycle centres. Examples of successful implementation of the multilateral approach in the fuel cycle back end have also been demonstrated, although it is evidently only first steps on a long way with many obstacles to reach industrial, public and political consensus in the area. However, to provide timely global answers to global challenges in nuclear power, modelling and analysing regional architectures based on the multinational/multilateral approach for the fuel cycle back end should be continued and intensified [3.52]. These activities are an important task within the terms of reference of SYNERGIES.

Participants in SYNERGIES represent a wide spectrum of countries with different levels of nuclear power development, including newcomers, nuclear energy technology holders and technology users. Armenia, Belarus, the Russian Federation and Ukraine considered a scenario within the framework of collaborative project SYNERGIES of regional cooperation in the fuel cycle back end. This scenario is a good example of hypothetical interactions for the fuel cycle front end and back end since it involves nuclear energy countries in different states of nuclear power development and deployment.

By the definition proposed for the use of the heterogeneous model [3.52], which can depict an NES comprising countries with various levels of nuclear technology development, Armenia, Belarus, the Russian Federation and Ukraine belong to different strategy groups. The Russian Federation belongs to the nuclear energy group which pursues a general strategy to recycle spent fuel (NG1). This group plans to build, operate and manage used fuel by recycling facilities and permanent geological disposal facilities for highly radioactive waste. Ukraine can be placed into a nuclear energy group which follows a strategy either to directly dispose of spent fuel or to reprocess it abroad (NG2). This group plans to build, operate, and manage permanent geological disposal facilities for highly radioactive waste in the state (in the form of used fuel and/or reprocessing waste) and/or works synergistically with another group to have its fuel recycled. Armenia and Belarus have a general strategy to use fresh fuel supplied from abroad and to send used fuel abroad for either recycle or disposal, or the back end strategy is undecided, being part of the nuclear energy group NG3. The complete case study can be found in Annex XII accompanying this publication.

3.3.10.2. Objective and problem formulation

The objective of this study is to explore the scale of one of the possible regional activities involving different country groups in the short term and to analyse scenarios for the hypothetical scenario of regional cooperation on the back end of fuel cycle.

The Russian Federation is an active participant of the regional and global multilateral cooperation and has plans for its expansion. More than 10 nuclear power units are under construction abroad and construction of another 20 new blocks are under negotiations. The Russian Federation is an established supplier of services of the fuel cycle front end. The State Atomic Energy Corporation “Rosatom” provides 8% of uranium mined, 17% from the production of fresh nuclear fuels, 22% of the uranium conversion and 40% enrichment services worldwide. In 2007, the International Uranium Enrichment Center (ICUE) was founded in Angarsk, Siberia, as an initiative of the Russian Federation, conducted under the auspices of the IAEA. The Russian Federation also has certain experience in implementing the fuel take back option when the leased fuel, once removed from the reactor and cooled down, is returned to the country of origin. Nuclear fuel cycle services provided by the Russian Federation are expected to be expanded under an appropriate political and economic environment. In present study it was assumed that the International Fuel Cycle Centre (IFCC) in the Russian Federation could also be established as a part of the international system of nuclear fuel cycle services.

Ukraine has considerable experience in the use and development of nuclear energy technologies at the initial stage of the nuclear fuel cycle (mining, conversion and fabrication of fresh fuel), but it is not planning to introduce fuel recycling technologies any time soon. With regard to the fuel cycle back end, long term storage of spent fuel is considered as a main option. The scenario in which spent fuel is reprocessed abroad is being considered as an alternative option to long term storage.

Armenia plans to commission one WWER-1000 unit and assesses as alternatives the implementation of an open fuel cycle or sending spent fuel to the Russian Federation for reprocessing and recycling.

Belarus plans to build two WWER-1000 units, and its main fuel cycle back end option is to send spent fuel to the Russian Federation for reprocessing and recycling.

3.3.10.3. Assumptions, methods, codes and input data used

Material flows within the regional model were simulated using the computer codes MESSAGE [3.36] and CYCLE [3.92]. Spent fuel flows to the Russian Federation from abroad were simulated in a regional synergistic model based on a multilateral approach. In parallel, a non-synergistic (national) model was used to compare effectiveness of multilateral and national approaches. Figure 3.200 shows the simplified scheme of material flows in a regional synergistic model.

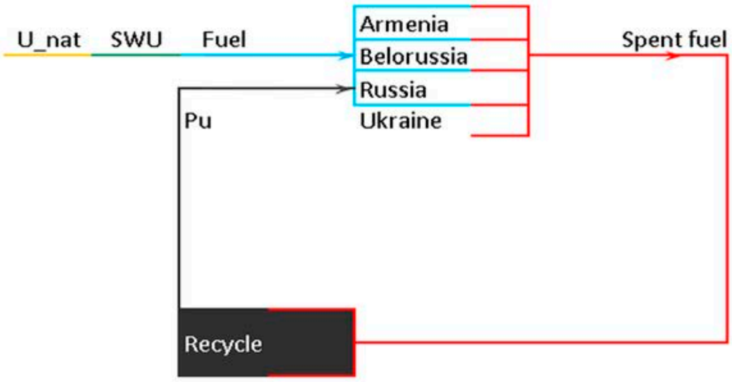


FIG. 3.200. Diagram of the regional synergistic model based on thermal and fast reactors and a closed fuel cycle.

The system includes the main fuel cycle elements: mining of natural uranium, conversion, enrichment, fuel fabrication, fuel irradiation and electricity generation at nuclear power reactors, cooling in-reactor and interim storage of spent fuel, reprocessing and fabrication of new fuel. The following types of reactor were considered in the system: WWER-440; WWER-1000; AWWER – advanced WWER; RBMK (high-power channel-type reactor); and SFR (breeding ratio of 1.23). Reuse of plutonium extracted from the fuel of thermal reactors WWER-440, WWER and AWWER and of fast reactors, is assumed. Other separated products (uranium, minor actinides and fission products) are kept in the storage facilities and can be further used or disposed of. Spent nuclear fuel of RBMK is not reprocessed and is kept in temporary storage.

The following assumptions were adopted to calculate the material flows in the model:

— The range of forecasting was limited by the year 2080.
— The modelling horizon was extended to 100 years to take into account edge effects, with linear interpolation on the total installed capacity.
— The simulation step was one year.
— Nuclear power capacities were input in a continuous manner.

The optimization code MESSAGE distributed by the IAEA [3.36] was implemented to analyse the flows of nuclear materials and assess economic considerations. MESSAGE is a large scale, dynamic simulation code that is used for the development of medium to long term energy scenarios and policy analysis. Strictly speaking, the scheme shown in Fig. 3.200 cannot be modelled with MESSAGE. It needs 'input–output' data for each reactor type and fuel cycle stage, which are not available without detailed physical calculations of the processes occurring in the reactor cores and decay of isotopes in the fuel cycle chains. However, application of the MESSAGE software can provide acceptable results for simulation of a group of similar scenarios with the condition to have corrected input data, with the use of a precise code.

CYCLE was developed by the Institute for Physics and Power Engineering as a precise code to simulate nuclide inventory evolution in reactors, storage facilities and other components of nuclear fuel cycles. Data from this tool were inserted into the MESSAGE user interface to provide greater reliability of the simulation results.

(a) Scenario of the WWER–fast reactor collaborative deployment aimed at solving the problem of accumulating spent fuel inventory

Scenario family C developed in SYNERGIES assumes collaboration aimed at solving the problem of accumulating spent fuel inventory between the countries that use LWR of the WWER and fast reactor types. This section provides the drivers and impediments at the initial phase of possible regional cooperation in the fuel cycle back end. A variant of the Russian NES arrangement which corresponds to Federal programmes under development is presented in Fig. 3.201.

The Ukraine SYNERGIES team provided to the IAEA a report on the state and prospects of nuclear power development in the country, including plans and programmes for construction of new nuclear power plants (see

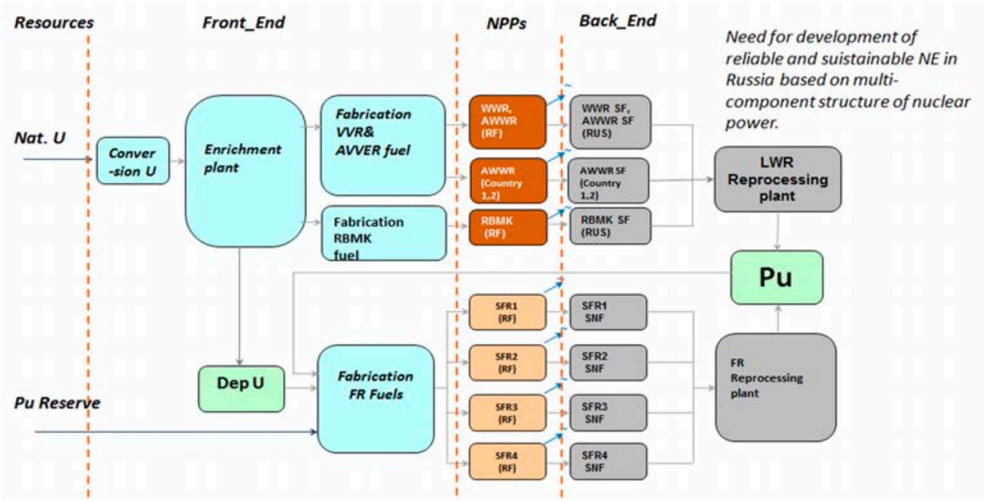


FIG. 3.201. A variant of the Russian nuclear energy system arrangement.

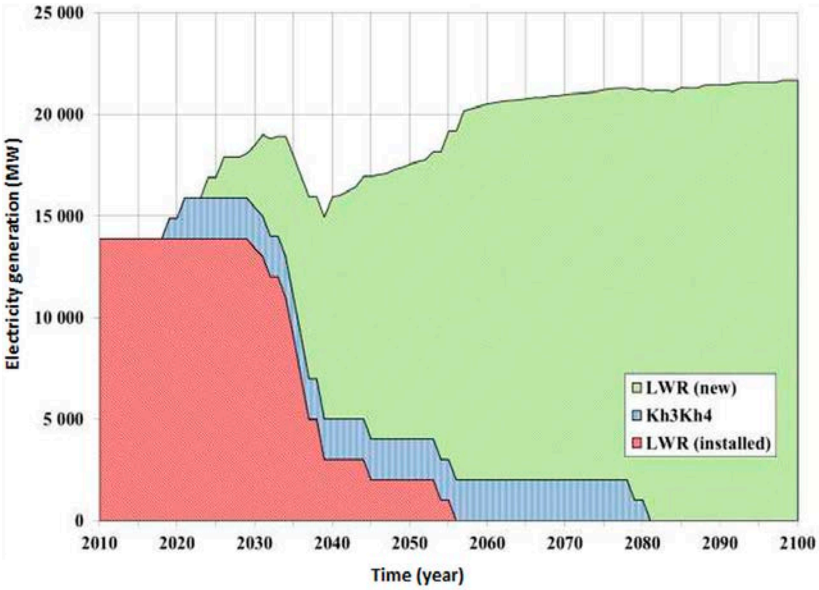
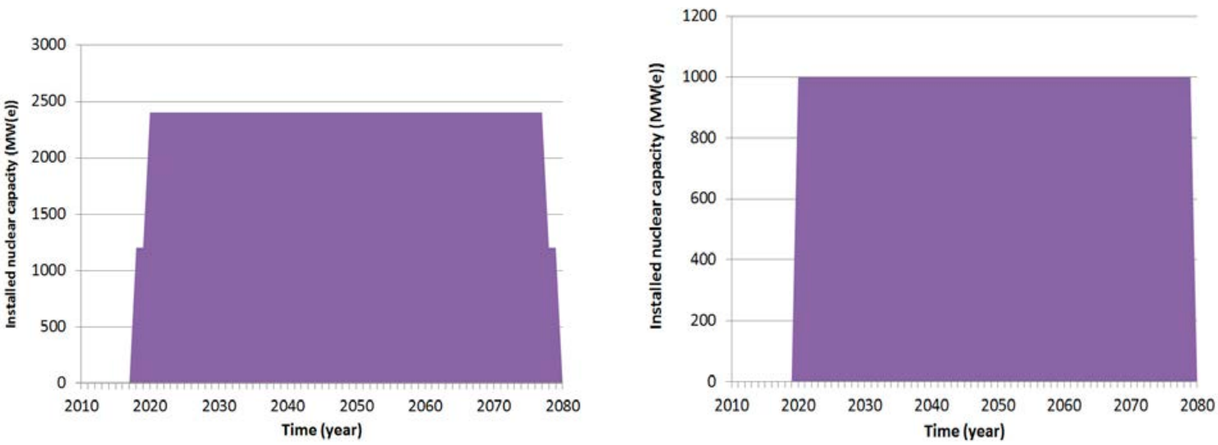


FIG. 3.202. A variant for nuclear power plant commissioning in Ukraine.



(a) Armenia (b) Belarus

FIG. 3.203. Variants for nuclear power plant commissioning.

Fig. 3.202). For the tasks of the study presented in this section, the front end and electricity generation of the Ukraine's NES were considered under a 'black box' approach in which output of spent fuel will be reprocessed. Plans and programmes for construction of a new nuclear power plant in Armenia and Belarus were also presented to the IAEA (see Fig. 3.203).

The study assumed that at the initial phase of regional collaboration in the middle of the century, possible spent fuel flows for recycling from abroad to the country where the IFCC is supposed to be located will be in the range of 150–400 t/year. Taking into account internal national studies, participants in the project agreed to consider the amount of spent fuel sent to an IFCC as a function of the national nuclear power plant deployment rate, which in turn depends on the overnight cost per kW(e) of nuclear power plant construction. US $3000 per kW(e) was considered as the minimum capital cost of nuclear power plant construction at which nuclear power is more competitive and more spent fuel could be sent for reprocessing abroad. US $5500 per kW(e) was considered as the high capital cost of nuclear power plant construction for which less spent fuel could be sent for reprocessing abroad.

(b) Scenario on the WWER–fast reactor collaborative deployment aimed at solving the problem of accumulating spent fuel inventory

As noted above, the Russian Federation belongs to the GAINS nuclear strategy group NG1 in which an IFCC could be established. Nuclear power remains an important part of the Russian strategy for the energy sector development up to 2030 [3.93] (see Table 3.43). One of the goals of the strategy is to decrease the high share (68%) of the fossil fuel power plants.

The strategy referred to in Table 3.43 was developed in the period of the country's economic recovery. Nowadays, the strategy is being revised. Economic development has slowed down and the planned rate of energy capacities commissioning will be probably reduced. Nevertheless, mutually beneficial 'win-win' collaboration with other countries in the area of nuclear energy is one of the priorities of the state policy and a driver for the national industry. Closure of the fuel cycle in the two component NES based on thermal and fast reactors is a near time prospect. In this context, two variants of the Russian two component nuclear power structure were developed (see Fig. 3.204): (a) an NES with a given share of SFR of 15% by 2050 and 50% by 2100 (low share of SFRs); and (b) an NES with a share of SFR defined by available plutonium for these reactors loadings (high share of SFRs).

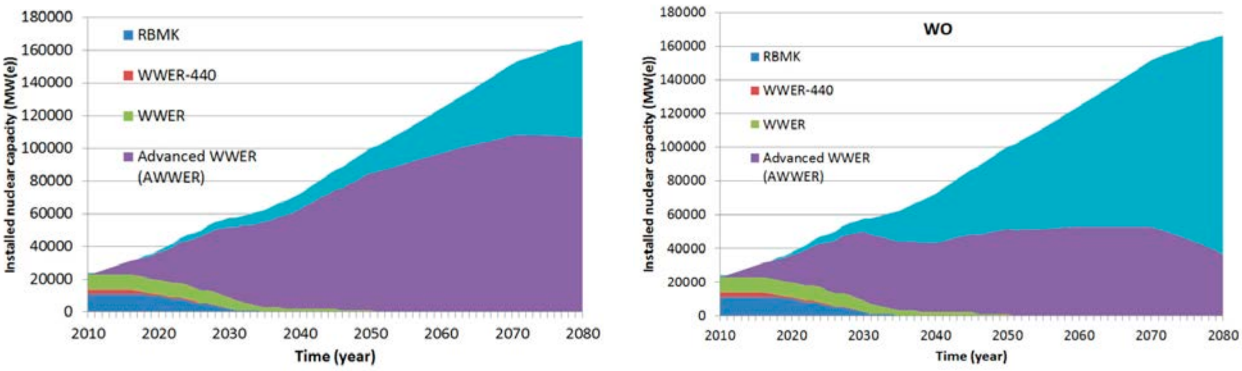
The input data on WWER-1000 necessary for the cases simulation were taken from the database developed in GAINS [3.52] and extended by the IAEA INPRO Section. It was assumed that the Russian fleet of fast reactors will consist of BN-1200 reactors. Some characteristics of the BN-1200 fast reactor are presented in Table 3.44 [3.94].

Three cases were considered within each variant:

(i) A non-synergistic case in which the Russian Federation reprocesses only spent fuel from nuclear power plants located in the Russian Federation, while spent fuel from nuclear power plants in Ukraine accumulate at local spent fuel storage facilities.
(ii) Synergistic case 1: Spent fuel from nuclear power plants located in the Russian Federation and Ukraine is reprocessed at Russian reprocessing plants. The amount of WWER spent fuel sent to the Russian Federation from Ukraine corresponds to the higher level of supply noted in Figs 3.205 and 3.206 as dSF3000.
(iii) Synergistic case 2: Spent fuel from nuclear power plants located in the Russian Federation and Ukraine are reprocessed at Russian reprocessing plants. The amount of WWER spent fuel sent to the Russian Federation from Ukraine corresponds to lower level of supply shown noted in Fig. 3.206 as dSF5500.

TABLE 3.43. STRATEGY OF THE RUSSIAN ENERGY SECTOR DEVELOPMENT UP TO 2030 [3.93]

	Years				
	2005 (fact)	2008 (fact)	2013–2015	2020–2022	2030
Installed power plant's capacity (GW(e))	216.3	224.9	239–267	275–315	355–445
Nuclear power plant capacity (GW(e))	23.7	23.8	28–33	37–41	52–62
Share of nuclear power plant capacity (%)	10.9	10.6	12	13	14

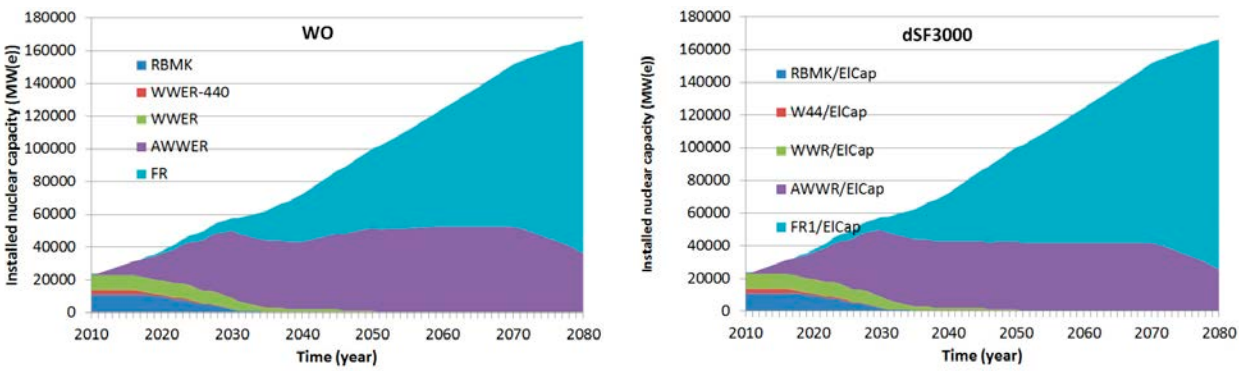


(a) (b)

FIG. 3.204. The structure of the electric capacity of Russian nuclear power for (a) low and (b) high shares of fast reactors.

TABLE 3.44. TECHNICAL CHARACTERISTICS OF THE BN-1200 FAST REACTOR.

Parameter	Data
Capacity (thermal)	2900 MW(th)
Capacity (electric)	1220 MW(e)
Coolant	Sodium
Core loading	46.9 t HM
Mass share of Pu in fuel	18.1%
Fuel campaign	4–6 years
Refuelling time	1.0 year
Breeding ratio	1.2



(a) (b)

FIG. 3.205. The structure of Russian nuclear power in the (a) non-synergistic case and (b) synergistic case for the variant of high share of fast reactors.

For each case the following indicators were calculated:

- Structure of nuclear power generating capacities;
- Cumulative consumption of natural uranium;
- Separation works;
- Rate of fuel production;
- Amount of spent nuclear fuel at storage;
- Rate of spent nuclear fuel reprocessing;
- Plutonium balance at storage facilities;
- Prices of natural uranium for the cases of high and low fast reactor shares.

Results of calculation and analysis performed for some of these indicators are discussed below.

3.3.10.4. Summary presentation and analysis of the results

(a) Structure of nuclear power generating capacities

Figure 3.205 presents the structure of the Russian nuclear power generating capacities calculated for the variant in which the share of SFRs is defined by available plutonium from WWER. The calculation of the indicators was performed for two cases: the non-synergistic case, in which only spent fuel from nuclear power plants located in the Russian Federation is reprocessed, noted as WO in Fig. 3.205(a); and the synergistic case 1, in which spent fuel from nuclear power plants located in the Russian Federation and Ukraine is reprocessed, noted as dSF3000 in Fig. 3.205(b). It can be seen that the addition of spent fuel from Ukraine at the amounts assumed does not significantly change the structure of Russian nuclear power. The impact of transition from synergistic case 1 to synergistic case 2 is even less. The share of SFRs in all three cases is presented in Fig. 3.206. The graph demonstrates that, within accepted assumptions, the maximum growth of the SFR share of Russian nuclear power to provide a balance of plutonium generation and consumption for synergistic cases is about 10%.

(b) Natural uranium demand for the case of high fast reactor share

Natural uranium demand for the non-synergistic case based on the national Russian programme of nuclear power deployment is shown in Fig. 3.207(a), and (b) demonstrates the demand for natural uranium in the synergistic case in which the WWER spent fuel from nuclear power plants located in the regional group is reprocessed, while separated plutonium from this spent fuel is fully recycled into the fuel of BN-1200 providing a high share of fast reactors in the structure the Russian nuclear power generating capacities.

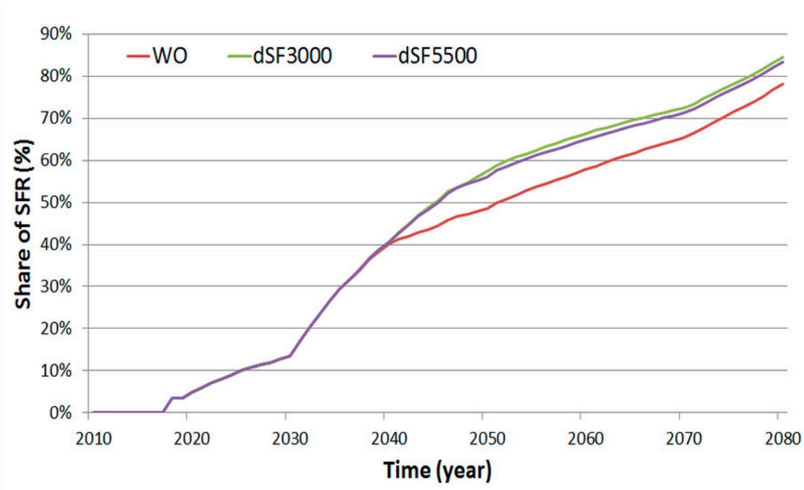
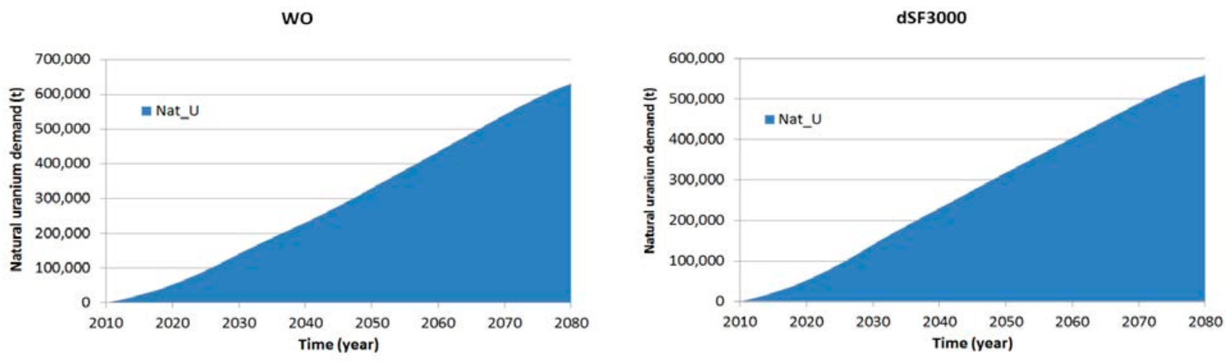
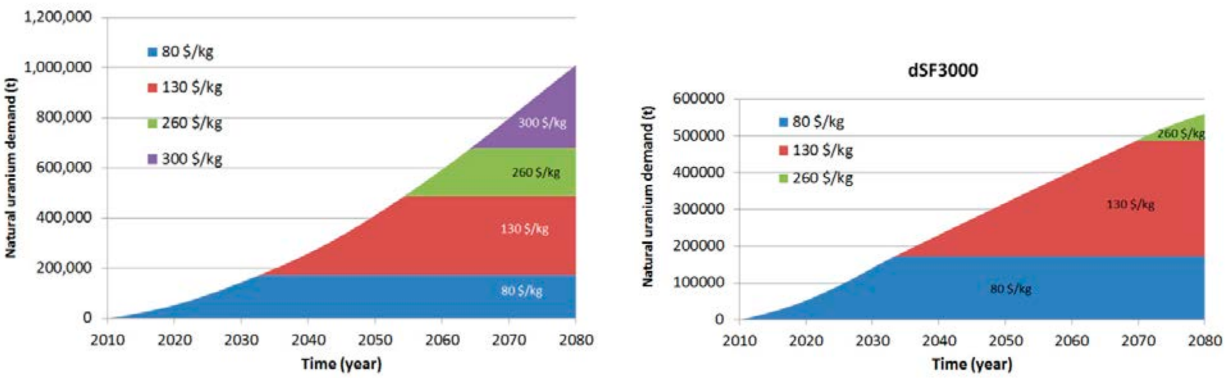


FIG. 3.206. The share of fast reactors in synergistic and non-synergistic cases for the variant defined by available plutonium for these reactor loadings.



(a) (b)

FIG. 3.207. Natural uranium demand for the (a) non-synergistic and (b) synergistic cases for the variant of high share of fast reactors in the Russian Federation as an NG1 country.



(a) (b)

FIG. 3.208. Natural uranium prices for (a) low and (b) high shares of fast reactors in the structure of Russian nuclear power capacity.

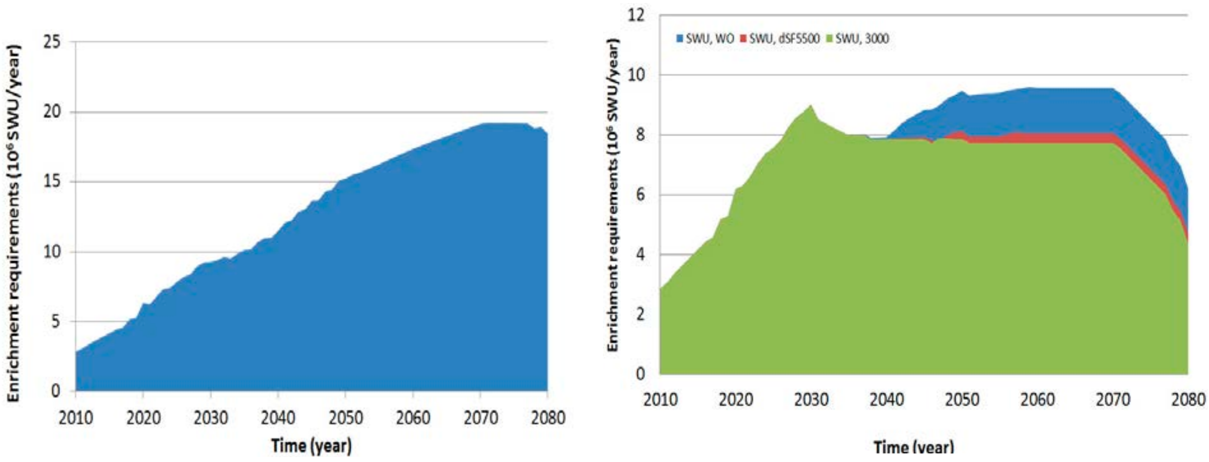
It can be seen in Fig. 3.206 that the synergistic case slightly reduces natural uranium consumption (~50 000 t) due to the use of additional plutonium in the MOX fuel instead of UOX. No perceptible impact on the natural uranium price was identified for these two cases. In contrast, changing in the structure of nuclear power generating capacities in the recipient country can affect the natural uranium price rather significantly.

(c) Natural uranium prices for the cases of high and low fast reactor share

Natural uranium demand in the case of low fast reactor share in the structure of the Russian nuclear power capacity is about 1 million t (see Fig. 3.204(a)), much higher than the approximate 550 000 t demanded in the case of high fast reactor share (see Fig. 3.204(b)). The increase in natural uranium consumption results in a related increase of uranium prices. As shown in Fig. 3.208, in the case of high fast reactor share in the recipient country, the partners of regional cooperation can benefit from the use of cheap natural uranium (US $80–130/kg) because of the utilization of more plutonium in fuels; in the case of low fast reactor share they can exhaust cheap uranium deposits and have to address more expensive uranium (US $260–300/kg).

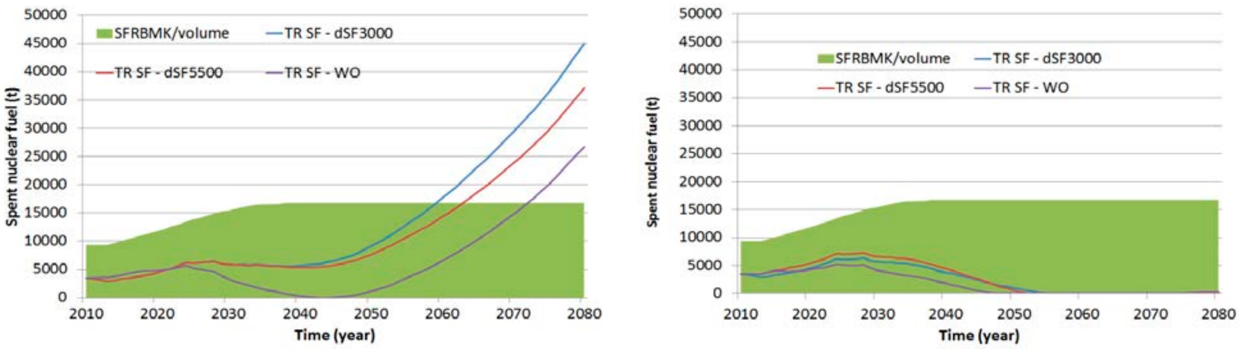
(d) Demand in enrichment services

Figure 3.209 represents the demand in enrichment services for the variant of Russian nuclear power structure with low and high share of fast reactors. An expected effect of reduction of the need in enrichment services under



(a) (b)

FIG. 3.209. Demand in enrichment services for the variants of Russian nuclear power structure with (a) low and (b) high shares of fast reactors.



(a) (b)

FIG. 3.210. Spent nuclear fuel accumulation in the Russian storage facilities for (a) low and (b) high shares of fast reactors.

transition to enhanced reprocessing is observed. As can be seen in Fig. 3.209(b), regional cooperation would add to the reduction effect in enrichment services, but not significantly.

Figure 3.210 demonstrates that accumulation of spent fuel in the country which takes this fuel from abroad is very sensitive to the ratio of thermal and fast reactors in its NES. There is a trend to accumulate spent nuclear fuel in the storage facilities of Russian reprocessing facilities in the variant with low share of fast reactors (see Fig. 3.210(a)). The contribution of spent fuel supply from abroad in this variant is rather perceptible. In the variant with high share of fast reactors, plutonium from spent fuel of Russian and Ukrainian WWERs could be reused by 2050 (see Fig. 3.210(b)). As mentioned above, at present there are no plans in the Russian Federation to reprocess spent fuel from RBMK reactors.

As it shown in Fig. 3.211, in the variant of high share of fast reactors, plutonium from storage can be used before all spent fuel is reprocessed. This means that plutonium has to be directed, after separation, to the fuel fabrication, without any delay. While demonstrating the potential of avoiding excessive accumulation of spent fuel and plutonium through regional collaboration, the study notes the economic impediments on implementation of this option in the near prospect. At present, technical and institutional procedures are not developed to the necessary details and the price formation in the area is not transparent. Long term intermediate spent fuel storage looks more attractive from an economic point of view, although it associated with some challenges in the long term.

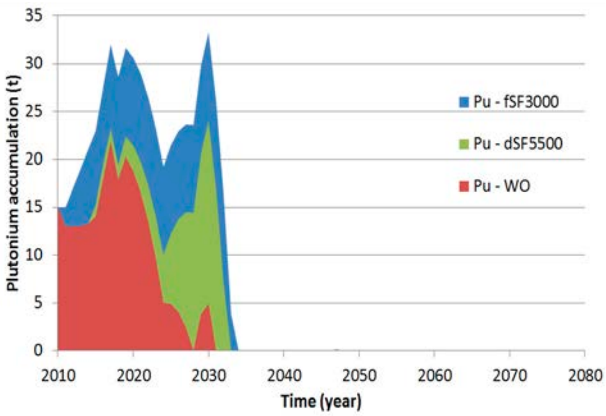


FIG. 3.211. *Plutonium accumulation in the variant of high share of fast reactors.*

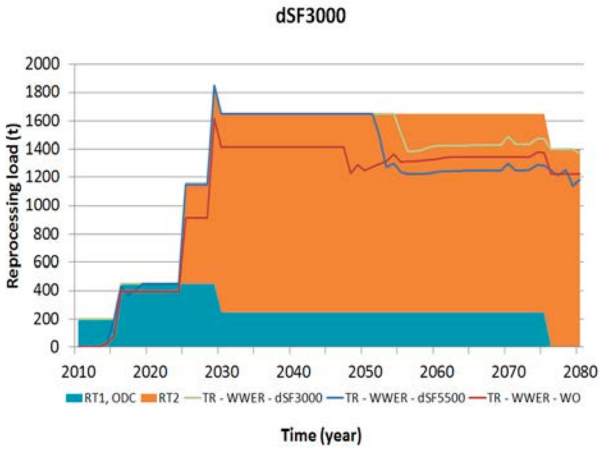


FIG. 3.212. *Load efficiency of WWER fuel reprocessing plants for the variant of low share of fast reactors.*

(e) Load efficiency of water cooled, water moderated power reactor fuel reprocessing plants

Figure 3.212 illustrates that within the assumptions made, the regional cooperation of Ukraine and the Russian Federation in the nuclear fuel cycle back end would not result in a significant impact on the capacities of Russian WWER fuel reprocessing plants planned for commissioning in the national closed fuel cycle programme. However, Fig. 3.212 also demonstrates that reprocessing capacities in the Russian Federation are fitted to the national programme, and they do not have necessary capacity reserves for further expansion of regional collaboration.

3.3.10.5. Conclusions

To date, only preliminary first steps are under way to develop regional and global collaboration on the fuel cycle back end. Within the SYNERGIES framework, it was agreed to consider a scenario of regional cooperation of the countries that use WWER type reactors, the technology held by the Russian Federation. Armenia, the Russian Federation and Ukraine have studied models for the initial stage of regional collaboration to demonstrate qualitatively and quantitatively the costs and benefits of such an approach. The analysis provided in this section briefly summarized results of the study as they are seen by the Russian SYNERGIES participants.

Multilateral collaboration on the fuel cycle back end is likely an inevitable solution on the path towards regionally/globally sustainable nuclear power. Some drivers and impediments in the specific example of regional cooperation on the NES based on the WWER type of thermal reactors and BN type of fast reactors were identified. Some of the drivers or benefits of regional collaboration include:

— Substantial savings of natural uranium for collaborating partners due to substitution of ^{235}U in UOX nuclear fuel of WWER by plutonium separated from UOX spent fuel of WWER and used in MOX fuel of fast reactors;
— The potential to collaboratively manage spent fuel and plutonium to avoid their excessive accumulation;
— Savings of financial and manpower resources for users on the development of expansive closed fuel cycle infrastructure while receiving all advantages of the cycle;
— Expansion of nuclear energy business for the technology holders and likely reductions to the cost of fuel cycle services;
— The possibility to utilize cheaper categories of uranium for both technology users and technology holders.

Along with the drivers some impediments for the regional collaboration were identified:

— Technical and institutional procedures are not developed to the necessary level of detail; the price formation in this area is not transparent and does not stimulate implementation of reprocessing abroad.
— Political and economic instability may hamper multilateral collaboration.
— Concerns over security of supply.

Participants of the project have applied the comprehensive methodology, databases, and tools established by the IAEA and INPRO for the scenario studies but recognize the need to their further development. In particular, more adequate simulation of regional collaboration requires more detailed information on the current realities. A number of issues require further research, such as:

— Reducing the uncertainty of initial data on the cost of the fuel cycle elements, including transport;
— Development of the methodological basis for the estimation of the spent fuel reprocessing products value (regenerated uranium and plutonium, among others);
— Clarifying the timing of spent fuel deliveries, storage times and conditions of reprocessing, the inventory of the returned materials and uncertainty of economic data, among other things.

The main conclusions for the prospects of regional collaboration are convincing. Further research should consider scaled demonstration of the recycling technologies (LWR MOX, fast reactor MOX) and their economics, including, among other things, the capital cost of BN versus WWER and the cost of fabrication for BN versus WWER.

3.3.11. Homogeneous and heterogeneous world model scenarios with WWER-Ss, SMRs and HTRs, including non-electrical applications

3.3.11.1. Introduction

Recently there has been increasing interest in LWRs operating with SCWR parameters and HTRs, including designs featured in the Generation IV R&D programme. Realization of these projects may increase nuclear energy competitiveness because of the high performance characteristics of the reactor designs with respect to thermal efficiency, resources use, safety and economics. Usage of SMRs is also feasible for countries with limited grids or remote regions and for energy supply diversification. In addition, these designs are being developed to take into account the possibility of their non-electrical applications, including for seawater desalination and heat production.

Previous IAEA studies have considered various nuclear energy scenarios, to different levels of granularity. Application of these technologies for a global approach was considered in Ref. [3.25]. A broad description of nuclear energy, its scale, resource limitations, group definition and possible future scenarios were presented in Ref. [3.52]. However, these studies did not consider in the detail the possibilities for collaboration between the countries developing technologies for WWER-Ss, HTRs and SMRs.

The present study prepared analysis of sustainable development for nuclear energy based specifically on the WWER-Ss, HTRs and SMRs, according to scenarios defined in previous studies. It has also assessed the expected effects these reactors could have on a NES based on a closed fuel cycle, in both homogeneous and heterogeneous scenarios. The complete case study can be found in the Annex XXI.

3.3.11.2. Objective and problem formulation

An overall objective of this study is to attempt to understand the capabilities of an LWR with high characteristics (WWER-S) to address challenges to nuclear energy for both open fuel cycles and closed fuel cycles that include fast reactors with a break-even breeding ratio of around 1. There are concerns related to management of large spent fuel volumes and limits to resources, among other things. The goal for HTRs and SMRs is to demonstrate the possibilities for collaboration, not only in the nuclear area, but in the entire field of energy system, by applying the HTR for technology processes without posing addition burden to the fuel cycle. This study seeks to address several questions:

— How does WWER-S affect the key indicators? (WWER-S has higher thermal efficiency and it was specially developed for work in closed fuel cycle; breeding ratio is ~0.8.)
— How will the structure of the NES change?
— How do HTRs and SMRs affect the material balances?
— To what extent is the NES structure sensitive to the level of collaboration between countries?
— What is the scale of HTR and SMR deployment under consideration by the country groups?

3.3.11.3. *Assumptions, methods, codes and input data used*

This study considers the time period from 1970 to 2100 under the following assumptions:

(i) Reserves of traditional natural uranium resources are accepted as 20 million t according to an estimation in Ref. [3.38]. Apparently, this value corresponds with the basic economical principle of INPRO of “affordable and available”.
(ii) Reprocessing capacities are assumed unlimited; that is, the whole volume of spent fuel is stored as needed, and then transported to a reprocessing facility where it is reprocessed completely.
(iii) Fast reactors are deployed in NG1 countries.
(iv) WWER-Ss will not be launched before 2025 because the WWER-S programme is still at the R&D stage.
(v) HWRs are deployed in NG2 countries; spent fuel from these reactors is planned for final disposal.
(vi) HTRs are deployed in NG3 countries, primarily for heavy industry applications, as it is assumed a significant share of global industry and production will be based in NG3. HTR spent fuel is not planned to be reprocessed; it will be finally disposed in NG2, if collaboration is pursued. About 5% of total nuclear energy capacities are required for non-electrical applications (e.g. for heavy oil production).
(vii) All country groups have demand for SMRs, as this reactor type is suitable for use in remote regions and regions with poor developed grids or a shortage of fresh water, for example. However, for simplification, this study assumes all SMRs are deployed in NG3 countries, representing only a small portion (5%) of overall nuclear energy production. Reprocessing of SMR spent fuel is not considered due to the its small quantity, but the expediency of doing so is noted (a large quantity of fissile isotopes is contained in SMR spent fuel).
(viii) The DESAE 2.2 code was used in the study. This mathematical modelling code was developed for systems analysis of high scale nuclear energy development. It performs calculations for regional, group and global considerations according to typical technological stages for open and closed fuel cycles. DESAE 2.2 includes models for many reactor types (both existing and planned) and fuel cycles, including scenarios involving a thorium cycle. It captures spent fuel management technologies including the MOX fresh fuel preparation stage, regenerated mixture fuel (REMIX fuel)[16], and the back end stages through final disposal. Its main task is to calculate material and energy balances within a mathematical framework of applied systems analysis, and then output data on quantity and characteristics for every technological stage.

3.3.11.4. *Summary presentation and analysis of the results*

(a) Open fuel cycle

Results of the calculation show the advantages of WWER-S for an NES. Their high parameters allow for more effective use of natural uranium and breed new fuel. Long term applications with WWER-S can allow a cumulative reduction in natural uranium consumption by up to 10–15% (see Fig. 3.213). The volume of accumulated spent fuel will be reduced as well (see Fig. 3.214). However, in a high usage scenario, the use of only one innovative technology will be insufficient to overcome the limitations of open fuel cycles. The expected 15% reduction of natural resources consumption will not provide sustainability for an open fuel cycle at high power production growth.

(b) Closed fuel cycle: Moderate case

To evaluate various approaches, closed fuel cycle scenarios have been studied on a global scale and as groups, with two ratios between the groups, 40–40–20% and 60–20–20%, respectively. It is suggested that application of WWER-Ss with a higher breeding ratio (0.8 instead of 0.4) may affect NES structure. For a homogeneous (global) scenario, the fast reactor share in 2100 is almost 42% of NES structure. This value is a maximum assessment of the fast reactor share in accepted conditions. For the non-synergistic heterogeneous case, the fast reactor share in 2100

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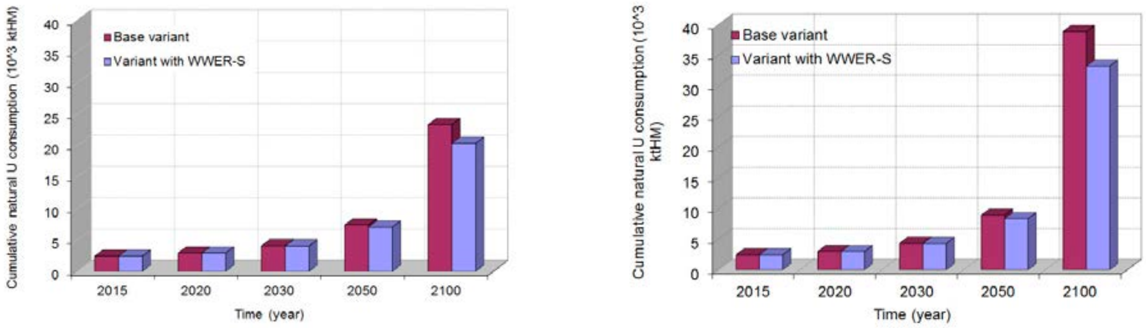
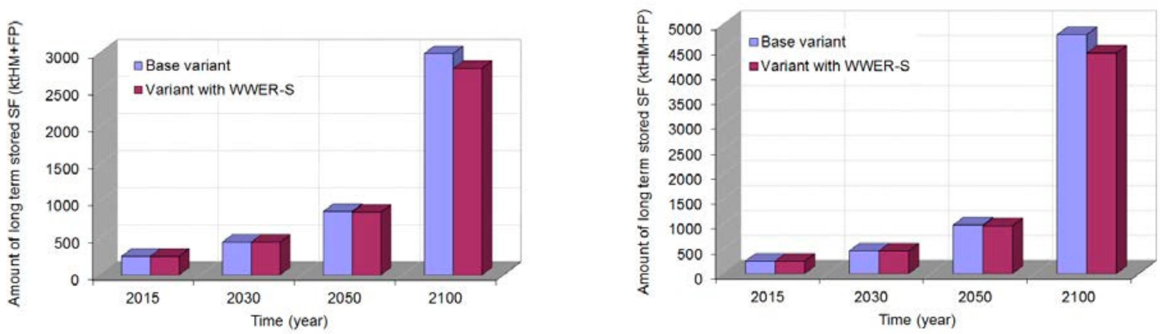
[16] REMIX fuel is obtained from the unseparated mixture of regenerated uranium and plutonium, which is a result of the reprocessing of the used nuclear fuel, with a small amount of enriched uranium being added. The method calls for the recycling of not only the plutonium that is contained in the used fuel but also of a residue of the ^{235}U.



(a) Moderate scenario (b) High scenario

FIG. 3.213. Cumulative natural uranium consumption.



(a) Moderate scenario (b) High scenario

FIG. 3.214. Amount of long term stored spent nuclear fuel.

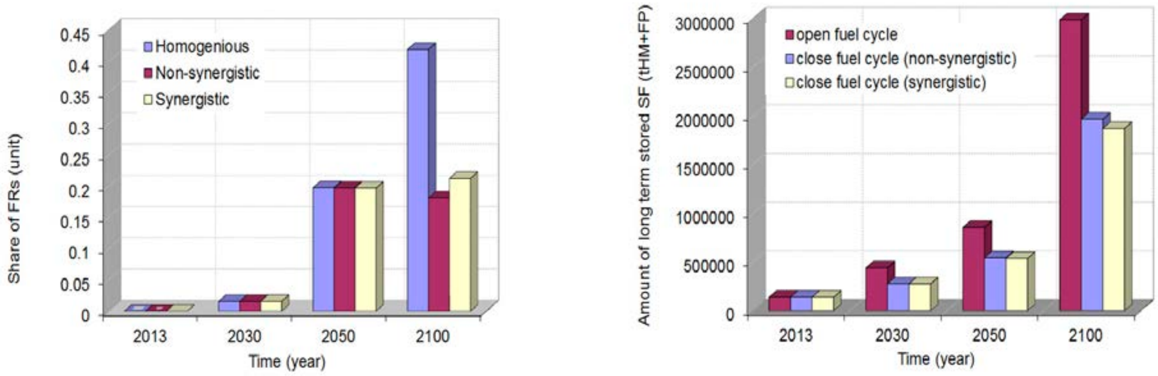
is approximately 18%, a lower figure because only 20% of thermal reactor spent fuel would be reprocessed. For the synergistic heterogeneous case, collaboration between groups allows for a slight increasing, whereby the share of fast reactors increases by 3% (see Fig. 3.215).

Considering a moderate power growth, 3 million t of spent fuel in 2100 will be accumulated under an open fuel cycle. Closing the fuel cycle allows a significant reduction of about 35–40%, depending on NG1 capacities and the level of collaboration between NG1 and NG3 (see Fig. 3.215). Reduction of spent fuel volume is mainly due to the closed fuel cycle; the effects of collaboration are less significant. In addition, one third of total spent fuel is from HWR operation and is not planned for reprocessing (this spent fuel has a lower level of radioactivity because of its low burnup).

A higher share of fast reactor, about 24%, is possible when considering other ratios between groups because of larger volume of spent fuel available for reprocessing. The difference between homogeneous and heterogeneous approaches additionally decreases when considering collaboration between groups. However, the difference between synergistic and non-synergistic considerations for heterogeneous scenarios is small because of accepted conditions for group collaboration: 50% of spent fuel from NG3 is reprocessed in NG1 (see Fig. 3.216).

(c) Closed fuel cycle: High case

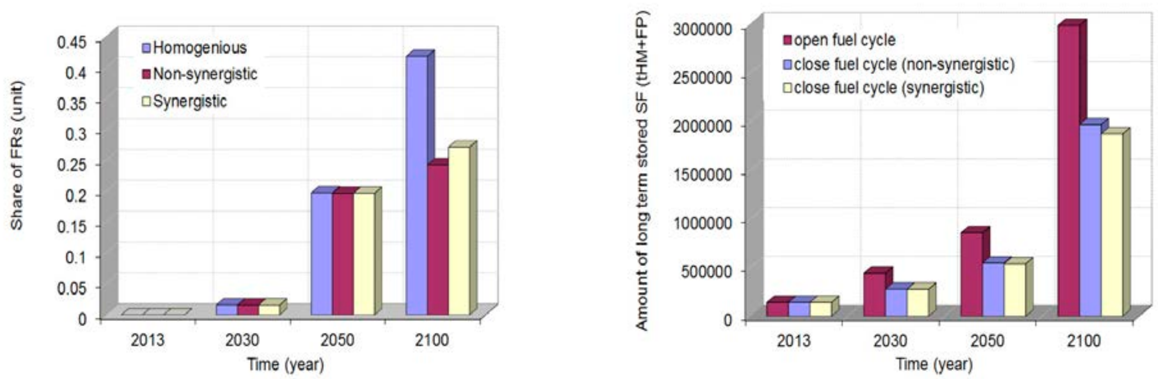
For high scenario, the fast reactor share is less by almost 10%. Apparently, it is caused by higher power capacities growth at the same volume of available plutonium for usage in fast reactors. Their share in 2100 in nuclear energy power structure is 33% for the homogeneous scenario (see Figs 3.217 and 3.218). This value is the maximum estimation of fast reactor share for accepted conditions. For the heterogeneous scenario, fast reactor share in 2100 is almost 14%. Redistribution of power capacity between groups is more significant for the high



(a) Fast reactor share

(b) Amount of long term stored spent fuel

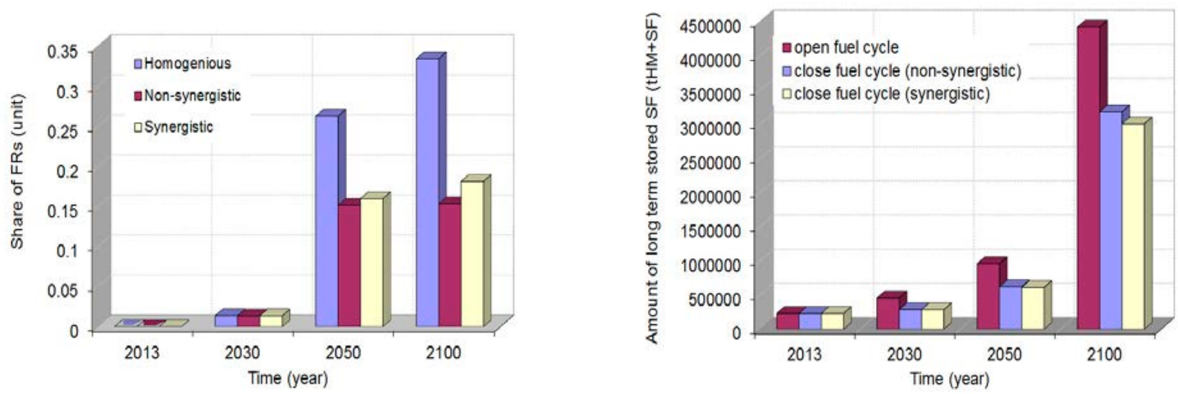
FIG. 3.215. Moderate scenario, group division 40–40–20.



(a) Fast reactor share

(b) Amount of long term stored spent fuel

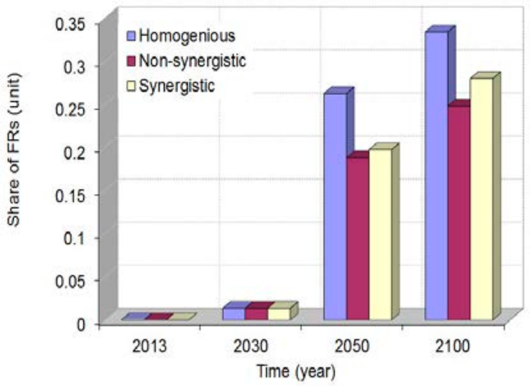
FIG. 3.216. Moderate scenario, group division 60–20–20.



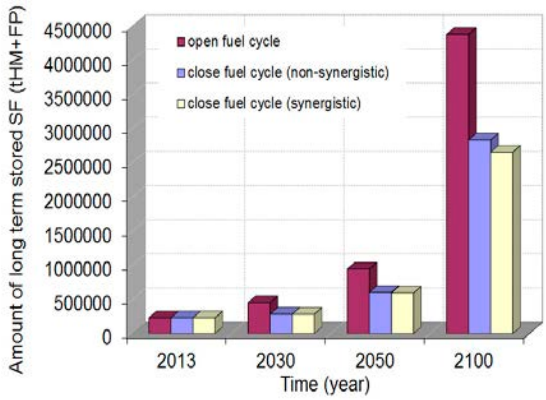
(a) Fast reactor share

(b) Amount of long term stored spent fuel

FIG. 3.217. High scenario, group division 40–40–20.

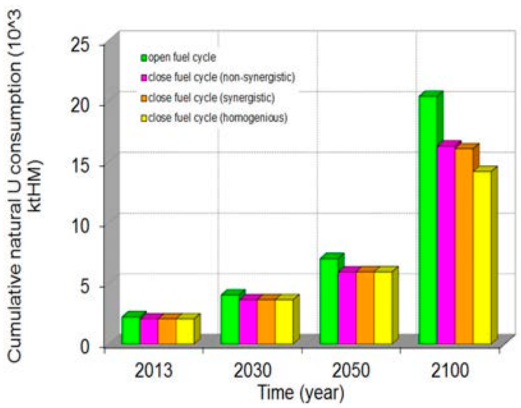


(a) Fast reactor share

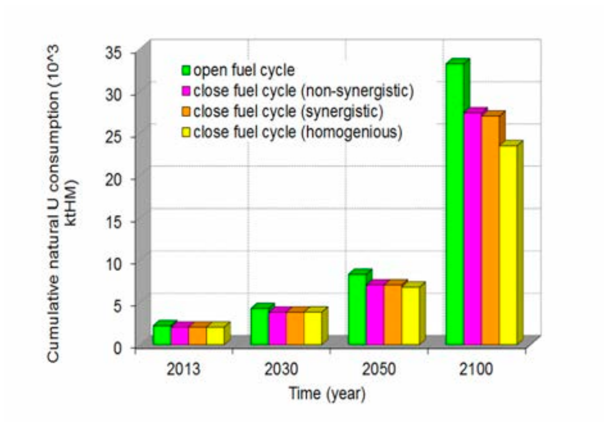


(b) Amount of long term stored spent fuel

FIG. 3.218. High scenario, group division 60–20–20.



(a) Moderate scenario



(b) High scenario

FIG. 3.219. Cumulative natural uranium consumption.

case. Extension of the NG1 share allows increasing fast reactors part in system structure almost to the maximum value characterizing the synergistic scenario. In a similar way, in the moderate case and considering collaboration between groups, the part of spent fuel from NG3 is reprocessed in NG1 with plutonium extraction for further usage in NG1 (see Figs 3.217 and 3.218).

Closing of the fuel cycle and putting into operation WWER-Ss, with more effective fuel use as resulted from supercritical water parameters, allow reducing the consumption of natural resources by 17%, on average, for moderate and high cases. Perspectives of more sustainable development of this system in respect to resources supply to the end of the century become possible because of the structure and scale of development require significantly fewer resources for realization.

Increasing the number of countries working in closed fuel cycle allows reducing the natural uranium consumption. The redistribution of power capacity between groups does not affect, practically, the size of natural resource shortages because the savings are insignificant (about 2.5%) for the high scenario. The main savings of uranium result from the closed fuel cycle realization in NG1 (see Fig. 3.219(a)).

Another picture is observed for the 60–20–20 ratio. Material balances for NG3 were not changed because the reactor share remained the same. Reactor share for NG2 decreased twice, which obviously led to a reduction of annual natural uranium consumption and separating works, among other things. It should be noted that HWRs remain in NG2 in full volume, resulting a minor increase of natural resources needs comparatively to NG3. At the same time, HWRs require less separating work. Increase of NG1 by 20% at the expense of WWER-S allows an increase of fast reactor share by 6% due to additional plutonium extraction from thermal reactors spent fuel.

Change of ratios between groups does not influence the cumulative needs as a whole and it remains almost constant independent on the approach (see Fig. 3.219(b)). In that case, the problem of resources exhaustion may be solved by using fast reactors with higher breeding ratios. Power capacity growth results in increasing spent fuel volume accumulation. A doubling of power capacities by the end of the century leads to spent fuel volume growth of 50%, which is to some extent compensated by the closing of the fuel cycle.

(d) Small and medium sized reactors

Figure 3.220 shows that thermal capacities are higher for the nuclear energy scenario with non-electrical applications. It is necessary to compensate power capacities for achievement of the same level of electricity generation while usage of nuclear energy for additional productions. Collaboration with NG3 implies two variants of spent fuel management: final disposal in NG2 and reprocessing in NG1, respectively. In the study framework, SMR spent fuel is not reprocessed because of its small share.

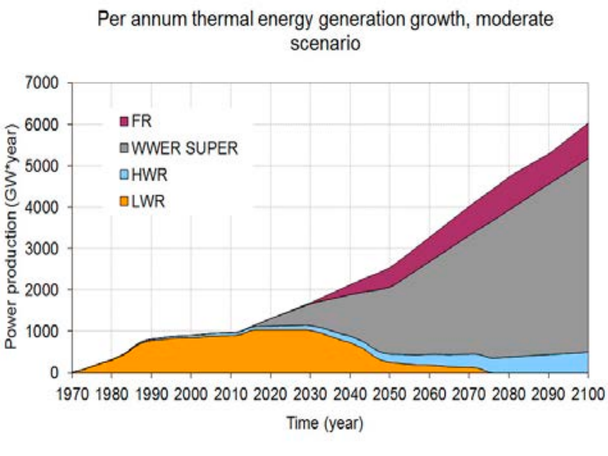
It is obvious that an increase of the power capacities leads to natural uranium consumption growth. However, non-electrical applications of nuclear energy insignificantly affect natural resources consumption. Besides, it should be noted that the difference may be minimal at the organization of SMR spent fuel reprocessing. It is accepted that the share of NG3 is 20% and SMR spent fuel is not reprocessing for all growth scales, so collaboration between groups and their dividing does not affect strongly on results for cogeneration and non-co-generation variants.

Analogously to uranium consumption growth, spent fuel accumulation proceeds more intensively for this system (see Fig. 3.221). Whole volume of spent fuel is in NG2 and NG3 in case of non-synergistic heterogeneous consideration. In spite of the fact that the HWR share is only 6%, part of the HWR spent fuel in the general structure is approximately 50%. Nevertheless, because of the low radioactivity level, decay heat of this spent fuel is insignificant (see Fig. 3.222).

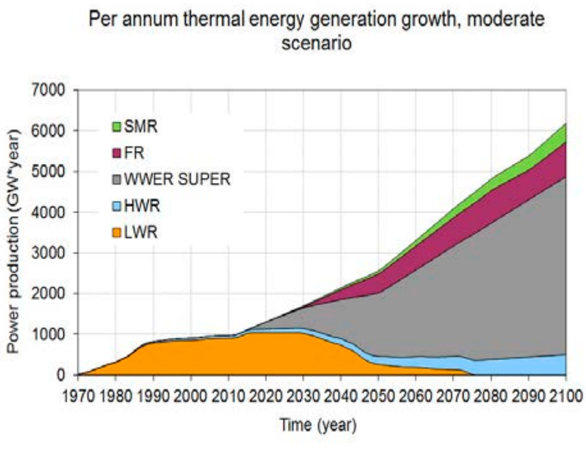
(e) High temperature reactors

Figure 3.223 shows that thermal production differs by 17% for considered scenarios. It is caused by the fact that most part of produced heat is used for non-electrical applications. It is necessary to compensate shortage of electricity production to have 2500 GW·year in 2100, by introducing more WWER-Ss. In this case, the share of thermal production will be 14% in the nuclear energy structure and share of electricity production will be only 3%.

Obviously, this significant growth of thermal capacity impacts natural uranium consumption increase. The volume of necessary uranium has increased by 14%. Nevertheless, first the material balances are affordable in the framework of accepted limitations on natural uranium reserves. Second, 1 billion t of heavy oil production is organized by more ecological methods using nuclear energy for non-electricity applications. At the same time, organic fuel consumption is reduced. The difference in uranium consumption might be higher, but effective fuel use



(a) Moderate scenario



(b) Moderate scenario with cogeneration

FIG. 3.220. Thermal power production.

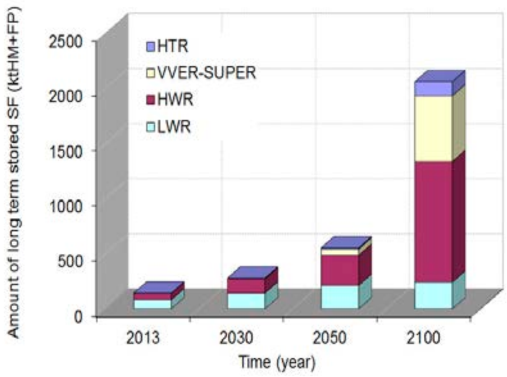


FIG. 3.221. Amount of long term stored spent fuel by reactor type (moderate scenario).

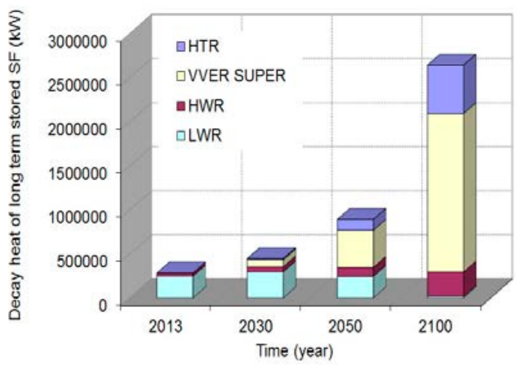
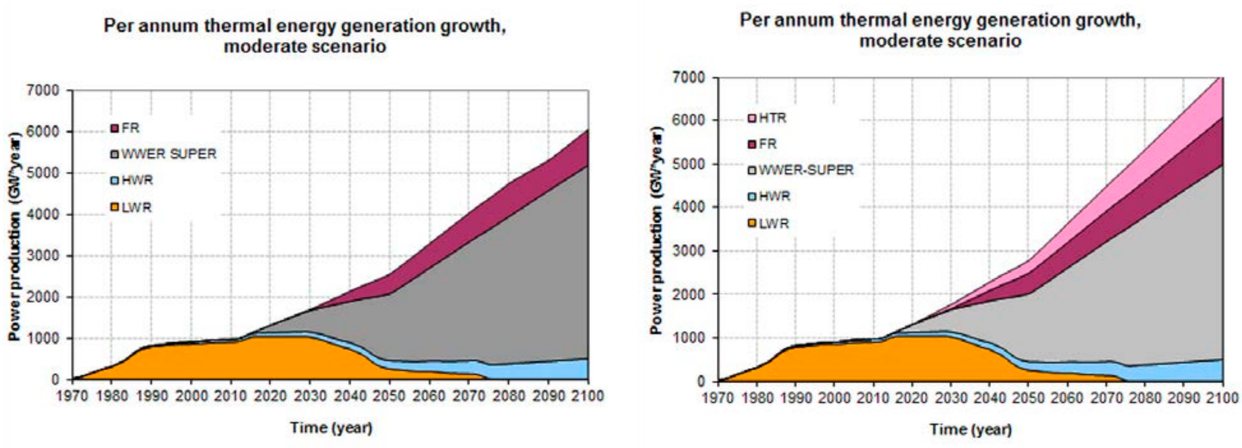


FIG. 3.222. Decay heat of long term stored spent fuel by reactor type (moderate scenario).



(a) Moderate scenario

(b) Moderate scenario with cogeneration

FIG. 3.223. Thermal power production.

in HTR compensates it. As a result, the difference in accumulation of spent fuel is insignificant. For the considered scenario, the spent fuel volume exceeds by 5% the result obtained for base scenario (only electricity applications of nuclear energy).

Figure 3.224 demonstrates the structure of spent fuel from different reactor types. As evident, HTR introduces insignificant changes in spent fuel structure and maximum falls to the share of HWR spent fuel. At the same time, the share of HTR decay heat in the general structure is more significant and achieves almost 20% because of the high burnup and, consequently, greater fission product accumulation (see Fig. 3.225).

HTR thermal power generation is 1000 GW·year and it is spent almost completely on heavy oil production and associated products for the considered scenario. The volume of different products is given in Table 3.45. Homogeneous and heterogeneous considerations give the extreme assessments reflecting upon maximum achievable as a result of effective work of the fuel cycle in the conditions of collaboration between countries or, contrary, those costs which certainly will appear in the absence of collaboration between countries. The complete analysis is presented in Annex XXI.

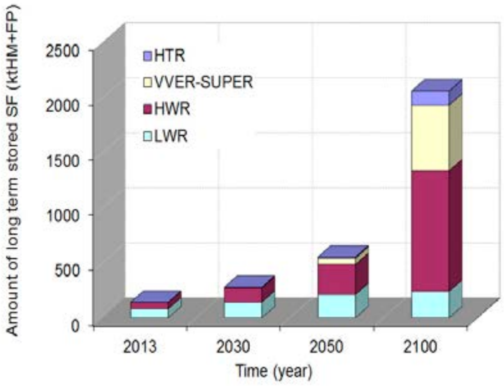


FIG. 3.224. Amount of long term stored spent fuel by reactor type (moderate scenario).

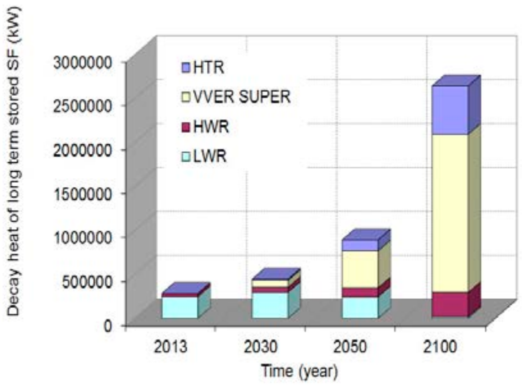


FIG. 3.225. Decay heat of long term stored spent fuel by reactor type (moderate scenario).

TABLE 3.45. PRODUCTION BALANCE FOR HTRs WITH 1000 GW INSTALLED CAPACITIES

Product	Value (kt/h)
Steam	580
Heavy oil	116
Hydrogen	8.1
Electricity (in GW(e))	76.7
Petrol	81.3
Other fuels and lubricants	34.7

3.3.11.5. Conclusions

The analysis performed shows that for the moderate case, the WWER-S is very good for an NES due to significantly better characteristics: thermal efficiency and fuel use — in comparison with existing thermal LWRs. The use of WWER-Ss is probably enough for moderate case realization in conditions of accepted uranium resources limitation, but an upgrade of thermal reactors only is not enough for the high case. Great volumes of spent fuel are accumulated for nuclear energy operating in open fuel cycle for both scales of NES development. It is necessary to watch closely storage facilities with spent fuel during tens and even hundreds of years. Besides, for the high scenario there is a shortage of natural resources independent on the used technologies.

For the moderate case, an NES with thermal LWRs and fast reactors with a breeding ratio of around 1 allow to operate in the framework of accepted limitations. But it is not enough for sustainable operation of NESs at high growth of power capacities. This structure does not solve the problem of resources supply in spite of a quite high WWER-S breeding ratio (~0.8) that allows increasing the plutonium production in the system. In this case, it is necessary to use not only innovative thermal reactors, but also innovative fast reactors with more effective parameters.

Collaboration between countries, both for reactor technologies supply and spent fuel management, allows the use of natural resources more rationally, reduce separating power capacities and volume of spent fuel, and the use of extracted uranium and plutonium. It should be noted that the ratio between groups does not significantly influence on NES key indicators.

A possibility of HTR and SMR non-electrical applications was considered in detail, and it was shown that operation of these reactor types in the system, in accepted volumes, will not significantly impact the fuel cycle and resources, while possibilities of their application are quite wide.

The conclusions of the study, extracted from NES scenarios analyses, correspond with the goals formulated for Task 2 of the INPRO collaborative project SYNERGIES. It was shown that, in the framework of the moderate scenario, it is possible to achieve sustainable nuclear energy development. It was appraised for synergistic collaboration with SMRs and HTRs considered in the nuclear energy structure, in case of their non-electric applications. For the high scale, it is not enough to use only upgraded thermal reactors in condition of accepted limitations for natural uranium resources. In this case, the search of sustainable development scenarios requires a more effective fast reactor type for better fuel usage. Detailed descriptions of the NES scenarios considered and analysis of the results are presented in Annex XXI.

3.3.12. Analysis of advanced European scenarios including transmutation and economical estimates

3.3.12.1. Introduction

The objective of this contribution is to analyse long term scenarios for closed nuclear fuel cycles in a European context, including economical estimates as additional reference results. Some intermediate results of this study have already been published in Ref. [3.95]. The analysis of long term sustainability of nuclear energy should consider transition scenarios from the current open fuel cycle or partially closed one to fully closed fuel cycles based on advanced technologies. Such study is expected to elaborate various aspects of transition scenarios, such as time period required to reach material flow equilibrium, the recommended number and time frame of introduction of fuel cycle facilities, the storage of nuclear material and generated nuclear waste, among other things. Moreover, there is an interest to improve these studies with economic analyses, as a necessary input to evaluate the realistic viability of new strategies.

This exercise analyses the transition from an existing LWR fleet to advanced fast reactors, taking also into account an intermediate stage of Generation III+ LWR deployment. It assumes that a representative number of EU Member States are involved, as in the PATEROS exercise [3.96]. The analysis of these fuel cycle scenarios is performed according to guidelines specified in the EU CP–ESFR [3.97] and ARCAS projects [3.98]. The complete case study can be found in Annex XXV on the CD-ROM accompanying this publication.

3.3.12.2. Objective and problem formulation

The main objective of this work is to analyse, in terms of available resources and economic implications, the impact of implementation of four reference scenarios on a European nuclear fleet under the assumption of constant nuclear electricity demand. This general objective requires the estimation of the following:

- Natural uranium and plutonium needs;
- Units of fast reactor and ADS facilities to achieve an equilibrium content of minor actinides in the fleet;
- The evolution of minor actinides for transmutation scenarios;
- The LCOE for each scenario and reactor type;
- Impact in the LCOE on the main components.

The study considers four nuclear fuel cycle scenarios for analysis starting in 2010 and spanning over 200 years. All four scenarios assume initial LWR Generation II reactors decommissioning periods for LWR_MOX as 2020–2025 and for LWR_UOX as 2020–2050. The particular descriptions for the four scenarios are:

- Scenario 1 (SCN-1) is the open fuel cycle reference scenario. The LWR plants are replaced after their assumed end of life by LWR Generation III reactors that operate until the end of analysis period (2210).
- Scenario 2 (SCN-2) assumes that LWR plants are replaced by LWRs Generation III after 2021, and by SFRs after 2040, until contributions to the total electricity are two thirds and one third, respectively, by 2050. Later, Generation III reactors are also substituted after end of life, and 100% of the electricity is obtained by using SFRs at the end of the century, which means around 79 reactors.
- Scenario 3 (SCN-3) is similar to SCN-2 except that 56% of the SFR plants are utilizing the minor actinide fuel for net transmutation (T-SFR technology), translating to around 44 reactors by the end of cycle. The balance of 44% SFRs (or 35 units) burn only plutonium.

— Scenario 4 (SCN-4) assumes that minor actinide transmutation is performed exclusively with ADS units, while SFRs are dedicated to plutonium burning and breeding. This scenario has the same assumptions as the SCN-2 with regards to LWR plants. The electricity generation by the ADSs is dependent on transmutation potential and availability of plutonium and minor actinides. A maximum amount of 51 ADS units is considered to be necessary to deploy, at some period of the scenario, while 37 units are required at the end of scenario, leading to an average of electric contribution of 3% along the cycle.

3.3.12.3. Assumptions, methods, codes and input data used

The fuel cycle scenarios are analysed using the TR_EVOL module developed by the Research Centre for Energy, Environment and Technology (CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas) [3.99]. The TR_EVOL is designed for studying various nuclear fuel cycle options considering deployment of various nuclear reactor technologies and associated nuclear materials over the short, medium or long term. The module takes into account the isotopic composition of nuclear materials such as fission products, minor actinides, plutonium and uranium at all stages of the nuclear fuel cycle.

The economic assessment module of the TR_EVOL provides the LCOE estimations using output from TR_EVOL mass balance. Furthermore, the possibility of uncertainties assessment in the economic estimations can be also carried out by the code. Scenarios consider five reactor types, named according to the fuel type. Their characteristics are taken from Refs [3.97, 3.98] and are presented as a summary in Table 3.46.

The fuel required for the cycle depends on the reactor type, specified as follows:

— LWR UOX for LWR Generation II, PWR/BWR type with UO_2 fuel (4.5% enrichment).
— LWR MOX for LWR Generation II, PWR/BWR type with MOX fuel (8.5% plutonium content).
— LWR GEN-III for LWR Generation III, PWR type with UO_2 fuel (4.5% enrichment).
— SFR (or T-SFR:) for a large core SFR with MOX fuel, plutonium average content close to 15%. T-SFR for minor actinides transmutation purposes in addition to plutonium breeding and electricity production (in this case, the assumed reference concept is a 2.5wt% minor actinides loading, homogeneously distributed in the reactor core, replacing the same amount of original uranium content).
— ADS for ADS, with inert matrix fuel (45wt% of heavy metal is plutonium, and 55wt% is minor actinides).

The initial spent fuel composition considered in the study is taken from current spent fuel legacy from seven European nuclear countries, assumed as associates in back end fuel management. The actinides accumulation term up to the year 2010 is provided by the EU CP–ESFR project specifications.

In terms of UO_2 fuel enrichment, there is no upper limit of capacity for SWU plants. The ^{235}U enrichment assumes tail assay of 0.25% up to the year 2020 and 0.20% afterwards. The fuel fabrication capacity is also assumed as unlimited in the current study.

The reprocessing plants considered in the scenarios are based on the fuel type (LWR, SFR and ADS). The reprocessing assumes minimum cooling period of five years for the irradiated fuel and takes place for one year. The

TABLE 3.46. SUMMARY OF ASSUMED PARAMETERS FOR REACTOR TECHNOLOGIES

Parameter	LWR UOX	LWR MOX	LWR GEN-III	SFR	ADS
Unit thermal power (GW(th))	2.965	2.965	4.4	3.6	0.4
Thermal efficiency (%)	34	34	34	40	32
Capacity factor	0.80	0.80	0.85	0.80	0.75
Unloaded fuel burnup (GW·d/t HM)	50	45	55	99	150
Unit lifetime (years)	40	40	60	60	60
Pu conversion ratio	0.42	0.66	0.48	1.08	1.00

Note: ADS — accelerator driven system; GEN-III — Generation III; HM — heavy metal; LWR — light water reactor; MOX — mixed oxide; SFR — sodium cooled fast reactor; UOX — uranium oxide.

reprocessing loss of 0.1wt% is considered for actinides, plutonium and uranium. The current exercise does not take into account the loss rate during fabrication stage, in accordance with the CP–ESFR reference scenario.

The LCOE consists of four components, averaged over time:

(i) Investment cost includes the overnight cost and financial costs split in interest during construction and interest for the financing.
(ii) Fuel cost represents the front end cost.
(iii) Operation and maintenance cost is the annual cost for running the plant depending on the installed capacity.
(iv) Decommissioning, dismantling and waste disposal (DDD) cost includes reactor plant dismantling, fuel waste final management associated to fuel interim and final disposal costs.

All costs, excluding the DDD cost component, are summarized in Annex XXV, which includes the best case unit costs for each item as taken from the ARCAS project (see table 2 of Annex XXV on the CD-ROM accompanying this publication). Uncertainties are taken from the OECD [3.9] and adjusted for inflation and currency conversion (2012 level price).

Concerning the fuel costs, the MOX and advanced fuel costs are explained by means of the structural assembly costs and a mixed reprocessed material compound cost in terms of newly fabricated fuel. The compound cost depends on scenario evolution and is obtained after assuming fixed unitary cost of spent fuel reprocessing. On the other hand, for UOX fuel type, the cost is based on costs of uranium concentrate, conversions, enrichment and structural assembly fabrication.

It is assumed that LWR UOX and LWR MOX are paid off at the beginning of all scenarios and, therefore, generation costs for such plants will include only fuel, operation and maintenance and DDD costs, without accounting for their investment costs.

Concerning final disposal storage, the storage limits are set by mass and thermal constraints of spent fuel packages being placed in the repository. A maximum number of four LWR UOX spent fuel assemblies were loaded in a waste package, and only one LWR MOX spent fuel per package. In the case of HLW obtained in advanced closed cycles as vitrified packages, these are considered individually stored in their own steel canisters.

With regard to the DDD cost, the first contribution is decommissioning and dismantling, for which an average value of 15% of reactor overnight cost is assumed. The second contribution is disposal, for which two phases are considered according to nowadays policies in many countries: interim disposal and final disposal, with corresponding costs each one. They are estimated using the TR_EVOL model and their averaged unit cost is shown in tables 3 and 4 of Annex XXV. It must be emphasized that such information has been obtained from other studies and additional consultations; they should be considered generic values, mostly for comparison among scenarios.

3.3.12.4. Summary presentation and analysis of the results

The analyses of fuel cycle scenarios regarding resource availability show that the SCN-1 (the reference scenario) requires approximately 3.3 million t U by 2210. Such uranium requirements do not pose a significant constraint since the present global energy demand is four times the energy demand considered in the scenario whereas the worldwide economically available uranium exceeds the uranium requirements by five times. The remaining three advanced fuel cycle scenarios are observed to require less than one third of the uranium resources required by the SCN-1 by the end of analysis period.

The analysis results on plutonium availability for advanced scenarios (SCN-2, SCN-3 and SCN-4) show that all three scenarios have a similar tendency due to consumption of available plutonium in SFR, T-SFR or ADS. The plutonium accumulation is more pronounced in near term and reaches peak value of approximately 1000 t HM in 2038 after which the first batch of advanced reactors undergoes commissioning and generates demand of plutonium for new MOX cores fabrication. Afterwards, the plutonium accumulation is caused by LWR Generation III and SFR breeding and reaches another peak value of approximately 1100 t HM in 2077. The second stage of advanced reactors commissioning spanning over 20 years reduces the plutonium availability after 2077. Subsequently, the presence of advanced systems consuming plutonium and minor actinides help in keeping the plutonium accumulation to a limited level until the end of analysed period.

The decommissioning and replacement of advanced reactors along the cycle leads to significant spent fuel unloading from retiring cores and has been taken into account during the analysis. It is pertinent to mention that, beyond 2110, the reactors with higher breeding ratios are not required, since the equilibrium of fuel cycle can be established using smaller breeding ratios. Therefore, the breeding ratios of around 1.01–1.03 were used for reactors after 2110 for maintaining the plutonium stock at a reasonable level for smooth cycle and avoiding excess plutonium accumulation in the storage.

The SCN-2, SCN-3 and SCN-4 utilize depleted uranium for fast reactor fuel fabrication. It is observed that there is no constraint on SFR fuel fabrication due to the depleted uranium as sufficient quantities of the depleted uranium are present for at least 1000 years. Moreover, the reprocessed uranium can also be utilized for fabrication of fast reactor fuel directly or fabrication of UO_2 fuel by its re-enrichment. Such options are not included in the current study due to associated complexities of flow and waste streams.

Transmutation performance of scenarios in Fig. 3.226 presents the plutonium and minor actinide accumulation in interim and final disposal storages by the end of cycle. Significant reduction in the plutonium inventory in disposal storages is observed for advanced scenarios employing fast reactors. The minor actinide inventory is considerably reduced only in SCN-3 and SCN-4, which utilize dedicated minor actinide transmutation technologies.

The HLW inventories in the interim disposal and final disposal storages for each scenario are presented in Fig. 3.227 by 2210. The HLW inventories include reprocessing losses, non-reprocessed fission products and actinides, spent fuel assemblies in the case of the scenarios. The results show that advanced cycle scenarios SCN-2, SCN-3 and SCN-4 observe significantly reduced HLW generation.

The economic results for all scenarios are summarized in the Fig. 3.228, which shows the LCOE values along with the contribution of individual LCOE components. It is important to mention that the LCOE was calculated by applying the unit costs resulting in best case for all scenarios for complete length of scenario period and duly averaged by energy and technology share.

Concerning HLW, it has been assumed to be temporarily stored in interim disposal before final disposal. Figure 3.229 shows the costs for HLW inventory for each scenario as displayed in Fig. 3.227. A significant difference between SCN-1 (once through scenario) and advanced strategies (reprocessing scenarios) can be observed from the figure. The interim storage costs are reduced by a factor of 3 for reprocessing scenario SCN-2 and by a factor of 3.6 for transmutation scenarios SCN-3 and SCN-4. These disposal costs are a component of DDD costs representing around 3.5% and 1% of LCOE for SCN-1 and SCN2, respectively, and around 0.7% for both SCN-3 and SCN-4.

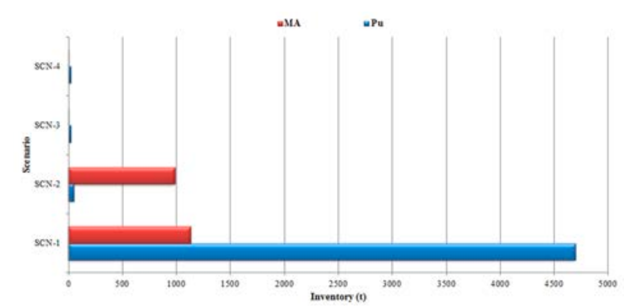


FIG. 3.226. Plutonium and minor actinide inventories in disposal facilities at the end of scenario cycle (2210).

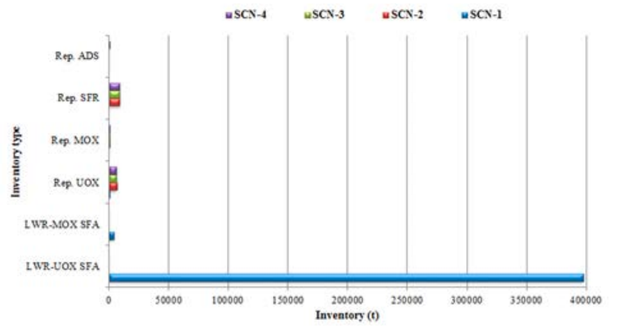


FIG. 3.227. High level waste inventories in disposal facilities at the end of scenario cycle (2210).

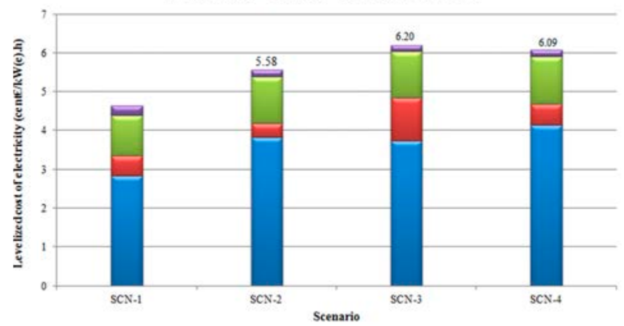


FIG. 3.228. Summary of economic results for all scenarios, based on data from Ref. [3.95].

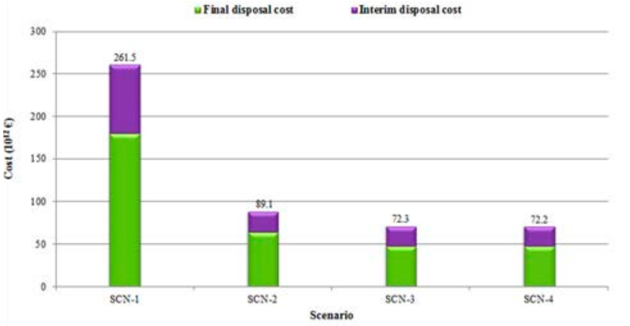


FIG. 3.229. Spent fuel/high level waste storage costs for interim and final disposal, based on data from Ref. [3.95].

3.3.12.5. Conclusions

The study simulated four nuclear fuel cycle scenarios including open fuel cycle and advanced fuel cycles of reprocessing and transmutation options using the TR_EVOL code for exploring the impact of advanced reactor, partitioning and transmutation technologies on resources availability and economics in the European context. The results confirm the feasibility of all considered fuel cycle scenarios regarding resource availability. No significant constraints were observed related to availability of natural uranium, depleted uranium, plutonium and minor actinides in the fuel cycle options.

It is observed that the transmutation strategy plays an important role in reducing the amount of minor actinides in the final disposal, and fast reactors significantly reduce the amount of plutonium in the disposal storages. The objectives of minimizing the plutonium and minor actinide inventories in repositories can be achieved by employing SFR for combined purposes of energy production and minor actinide transmutation. Another plausible strategy for consideration is using SFR for electricity production and ADS dedicated to minor actinide burning.

As comes to economics, the estimates show an average increase in LCOE by 20% for fuel cycle strategy employing SFR (SCN-2) over the whole period, and approximately 35% for transmutation scenarios correspondingly. The investment cost was found to make a prime contribution to electricity cost, being responsible for 60–69% of the total cost. It was also found that the cost of the HLW disposal can be reduced by approximately a factor 4 in a strategy using fast reactors and a 5 time transmutation strategy. This cost constitutes a relatively small share of LCOE (3.7% for SCN-1 and <1% for advanced scenarios).

3.3.13. Scenario with the WWER–fast reactor collaborative deployment

3.3.13.1. Introduction

The research work was performed according to Task 1 of the collaborative project SYNERGIES. The general objective was the elaboration of proposals for areas of international cooperation regarding the development of the NES in Ukraine in the medium and long term, using Generation III+ and Generation IV reactors, spent fuel reprocessing, and international centres for long term spent fuel storage and disposal. This research was carried out to facilitate a national vision of nuclear fuel cycle development. The complete case study can be found in Annex XIII on the CD-ROM accompanying this publication.

3.3.13.2. Objective and problem formulation

About 47% of the electricity in Ukraine is produced through domestic nuclear generation. The current NES is based on an open fuel cycle featuring four nuclear power plants (13 WWER-1000s and 2 WWER-440s) and transport of spent fuel abroad for long term storage and (potential) reprocessing. One nuclear power plant (Zaporizhzha) features a dry storage facility for the long term storage of spent fuel for up to 50 years. Fuel management is performed according to a ‘wait and see’ strategy. Accordingly, the Government has approved the construction of a centralized spent fuel dry storage facility of 5650 t HM. In addition, five LWRs operating with UOX fuel are to be commissioned by 2030, in accordance with the basic scenario of the updated energy strategy of Ukraine. A large amount of spent fuel will be accumulated by 2100.

The main objectives of this study were to develop a way for Ukraine to decrease spent fuel accumulation through implementation of fast reactors within the Ukrainian nuclear infrastructure. Proposals for a revised spent fuel management strategy are under development.

3.3.13.3. Assumptions, methods, codes and input data used

(a) General assumptions for nuclear energy

The energy system of Ukraine was modelled by generation forms, independently of specific power units and regional features. Nuclear generation, however, is represented by different reactor types. Economic parameters (e.g. price for resources and capital construction) are given in momentary prices (e.g. overnight cost). The modelling of non-nuclear energy was performed using the following boundary conditions:

— Solar and bioenergy power plants come with very small contributions to electricity production and do not affect significantly the energy mix of the country. Alternative and renewable energy sources are represented in the model as hydropower, wind and solar power.
— Renewable energy resources (e.g. hydro and wind) are unlimited in volume and have zero costs — only the commissioning rate of the generation capacities is limited.
— Coal reserves are sufficient to cover energy needs in full scope and thus are considered to be unlimited. The mining rate is also unlimited, and coal import is allowed if necessary.
— Gas for energy generation is imported, therefore its reserves are unlimited, and the supply rate is also unlimited.
— Electric power losses in the grids are decreased in accordance with the draft of the updated Energy Strategy till 2030, then they remain unchanged until 2050.
— The modelling period was up to 2100.

Modelling of the NES of Ukraine was performed using the following boundary conditions and assumptions:

— The initial condition of the nuclear energy sector of Ukraine is the beginning of 2012.
— Nuclear generation is represented absolutely as a basic component of the energy system of Ukraine.
— Nuclear share in the energy mix of Ukraine should not exceed 50%.

(b) Assumptions for the nuclear fuel cycle analysis

The assumptions for the nuclear fuel cycle analysis include the following:

— Five LWRs operating with UOX fuel are commissioned by 2030 (in accordance with the basic scenario of the energy strategy of Ukraine on 2013).
— There is a possibility for shipments spent fuel to a regional reprocessing centre.
— A closed fuel cycle based on fast reactors is possible after 2030.
— There is a possibility for annually commissioning no more than one reactor of any type after 2030.
— Commissioning of LWR with UOX fuel, LWR with MOX fuel, HWR with regenerated uranium and fast reactor is defined by the model after optimization.
— Reprocessing of LWR and fast reactor spent fuel is possible.
— MOX fuel application is possible after 2030; 25% of the core will be loaded with this type of fuel.
— The commissioning of HWR with reprocessed uranium fuel is possible after 2030.
— An opportunity of LWR spent fuel disposal is considered (at US $600/kg HM), with no constraints regarding the repository capacity.
— An opportunity of MOX spent fuel disposal is considered (at US $600/kg HM), with no constraints regarding the repository capacity.
— HWR spent fuel (reprocessed uranium fuel) is transported for disposal at the cost of US $600/kg HM, the repository capacity is not limited.
— The possibility of spent fuel reprocessing is admitted starting from the modelling period.

(c) Code and methods

The modelling of the energy system is performed by means of MESSAGE software [3.36]. Input data are presented in the following.

(i) Uranium resources

For energy system modelling purposes, natural uranium resources of Ukraine comprise 477 000 t (see Table 3.47). Nuclear power plant demand in uranium is covered by domestic reserves.

TABLE 3.47. PRICE RANGES OF URANIUM RESOURCES IN UKRAINE

Price range (US $/kg)	Resources (thousand t)
<80	135
<100	64.5
<120	22.5
<150	255

TABLE 3.48. FUEL FABRICATION COST

	Cost (US $/kg HM)
LWR (UOX)	300
LWR (MOX)	1500
HWR (REPU)	200
FR (BN-800)	300 (blanket) 2000 (core)
FR (BN-1200)	300 (blanket) 2400 (core)

Note: FR — fast reactor; HM — heavy metal; HWR — heavy water reactor; LWR — light water reactor; MOX — mixed oxide; REPU — reprocessed uranium; UOX — uranium oxide.

(ii) Uranium conversion and enrichment

For the modelling purposes, the cost of conversion services in 2013 was considered to be US $10/kg HM. The uranium conversion phase is considered as a service. Uranium enrichment is also considered as a service that costs US $130/SWU and is purchased at the global market, which is assumed to be unlimited.

(iii) Fresh fuel fabrication

Fresh nuclear fuel fabrication for LWRs is considered as a service that is purchased at US $300/kg HM (see Table 3.48). In 2008, average PWR nuclear fuel fabrication costs were US $250/kg HM. MOX fuel fabrication for LWRs is considered as a service purchased at US $1500/kg. The cost of blanket fabrication based on depleted uranium is US $300/kg HM. MOX fuel is used in fast reactor cores, as fabricated from depleted uranium derived from uranium enrichment tailings and plutonium resulting from spent fuel reprocessing. The cost of MOX fuel fabrication for fast reactor cores is US $2000/kg HM. Technical and economic parameters of the reactors are given in Table 3.49.

(iv) Spent fuel management

The spent fuel management input data is given in Table 3.50. The centralized spent fuel storage facility may be used as a temporary one (until postponed decision is implemented). The cost will be US $350/kg HM and includes capital costs, operation and maintenance costs and decommissioning costs. The commissioning of centralized spent fuel storage facility is planned in 2015, and its capacity makes up 5650 t. The cost of direct spent fuel disposal is estimated at US $400–1600/kg HM. The Ukrainian fuel cycle modelling considers spent fuel disposal as a service that costs about US $600/kg HM.

TABLE 3.49. TECHNICAL AND ECONOMIC PARAMETERS OF THE REACTORS

Parameter	WWER-1000	ALWR (WWER-1200)	LWR (MOX)	FR (BR = 1.19)	HWR
Thermal capacity (MW(th))	3 000	3200	3 200	2 900	2 064
Electrical capacity (MW(e))	1 000	1 120	1 120	1 200	728
Efficiency factor (%)	33	35	35	42	35.3
Capacity factor (%)	78	90	90	90	90
Fuel enrichment (%)	4.7	4.7	7% (Pu)	18.2 (Pu)	0.9
Av. burnup in fuel assembly (GW·d/t)	60	60	60	113	13
First load (t HM)	75.510[a]	72.844[a]	17.78 (MOX)[b] 53.35 (UOX)	General/Pu 41.5/7802	88
Annual reload (t HM)	16.677[c]	16.088[c]	3.93 (MOX)[b] 11.78 (UOX)	General/Pu 8.05/1.513	52.113
Construction costs (US $/kW)	3 400	5 000	5 000	6 000	4 000
Fixed costs (US $/kW) [3.100]	69.3	69.3	69.3	69.3	55.0
Variable costs (US $/MW·h) [3.36]	0.5	0.5	0.5	0.5	0.5
Operation lifetime (years)	50	60	60	60	35
Construction period (years)	6	6	6	6	5
Nuclear fuel fabrication (US $/kg)	300	300	1 500	2 400	200
Spent fuel disposal costs (US $/kW)	600	600	600	—	600
Reprocessing costs (US $/kg)	2 000	2 000	2000	2 200	—
Disposal costs for the products derived from spent fuel reprocessing (minor actinides, fission products) (US $/kg)	300 10 000	300 10 000	3 00 10 000	300 10 000	—

Note: FR — fast reactor; HM — heavy metal; HWR — heavy water reactor; LWR — light water reactor; MOX — mixed oxide; REPU — reprocessed uranium; UOX — uranium oxide; WWER — water cooled, water moderated power reactor.

[a] 163 fuel assemblies × 545 kg × 0.85 = 75 510 kg (× 0.88 = 78 174.5).

[b] 25% MOX fuel is loaded into the core.

[c] 36 fuel assemblies × 545 kg × 0.85 = 16 677 kg (× 0.88 = 17 265.6).

TABLE 3.50. CENTRALIZED SPENT FUEL DESIGN CAPACITY

Reactor type	No. fuel assemblies
WWER-1000	12 010
WWER-440	4 519
Total design capacity	16 529

(v) Light water reactor spent fuel reprocessing

The LWR spent fuel reprocessing is the following:

— For utilization in CANDU reactors: LWR spent fuel reprocessing is considered as a purchasable service that costs US $2000/kg.
— For utilization in fast reactors: LWR spent fuel is reprocessed with a purpose to extract plutonium and to fabricate MOX fuel to be used in fast reactors. LWR spent fuel reprocessing for fast reactor fuel fabrication is considered as a purchasable service that costs US $2000/kg HM.

(vi) Fast reactor spent fuel reprocessing for reprocessed uranium utilization in fast reactors

After being exposed to radiation in fast reactors, spent fuel may be reprocessed for repeated extraction of plutonium and MOX fuel fabrication to be loaded in the fast reactor core. The following assumptions are considered in relation to spent fuel used in fast reactors:

— All fast reactor spent fuel is reprocessed, but its disposal is not considered.
— After spent fuel reprocessing, plutonium is used for fast reactor fuel fabrication.
— After fast reactor spent fuel reprocessing, uranium is subject to storage for an unlimited period of time.
— In the model, there is no difference between spent fuel of the core and spent fuel of the blanket.
— After spent fuel reprocessing, minor actinides and fission products are subject to final disposal.

Fast reactor spent fuel reprocessing for further application in fast reactors is considered as a purchasable service that costs US $2200/kg.

(vii) Disposal of high level products derived from reprocessing

The model assumes that the repository capacity is not restricted, and the cost of HLW disposal is in the ranges of US $2500–12 500/kg FP, with US $10 000/kg FP being used for the model.

(viii) Non-nuclear generation and electricity consumption

The projected electricity consumption in Ukraine until 2100 is presented in Fig. 3.230.

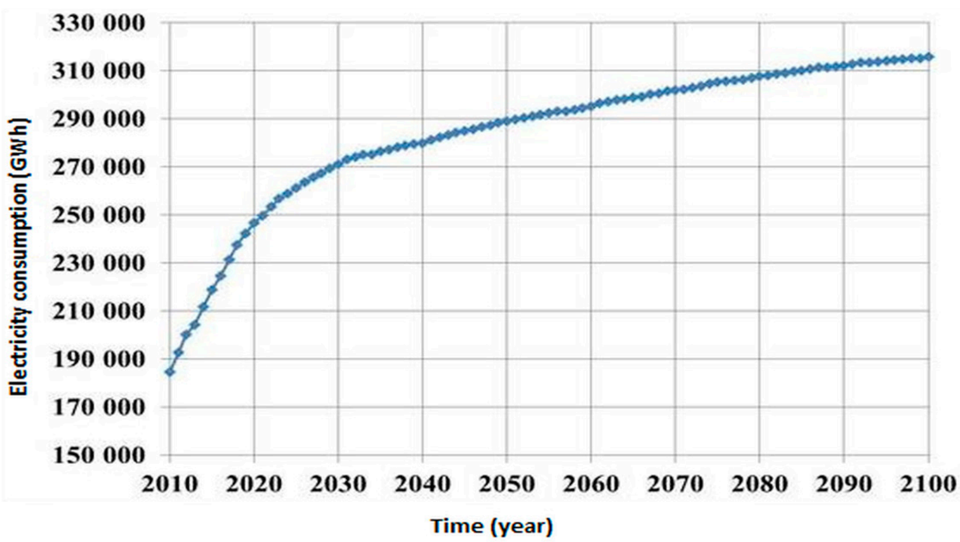


FIG. 3.230. Projected electricity consumption in Ukraine until 2100.

(ix) Electricity production

The installed capacities structure is actual for 31 December 2011 [3.101] and the electricity generation structure [3.102] in Ukraine are presented in Tables 3.51 and 3.52. Coal fired power plants have the major share in the installed capacities at about 50%, and nuclear power plants cover about 25%. The share of solar and wind power plants comprises 0.35% and 0.23%, respectively. It should be noted that most of the thermal power plants were commissioned in 1960–1980 [3.102] and their modernization should be started in the coming years. The commissioning of most nuclear power plants occurred in 1980–1990. Nowadays, the activities on lifetime extension for nuclear power units are carried out.

(x) Non-nuclear energy

Ukraine enjoys almost all fossil and renewable primary energy resources; however, their power potential is very different. Since 2000, the coal consumption for electricity generation was of about 40–50 million t of standard fuel, which corresponds to the mining capabilities of Ukraine. However, the coal mined in Ukraine is difficult to access and a lot of investments are required for new technologies deployment that could make the coal mining less expensive. Coal fired power plants are presented as a technology in the model with the following parameters:

— Capacity factor is about 55%.
— Capital construction costs are US $1600/kW.
— Construction period is four years.
— Fixed costs are about US $57/kW of installed capacity per year.
— Variable costs are about US $4.5/kW·h of generated electricity at specific coal price correlated with generated energy and estimated at US $107/kW·year (US $100/t).
— Construction and modernization rate of coal fired power plants does not exceed 2000 MW per year.

TABLE 3.51. INSTALLED CAPACITIES STRUCTURE IN UKRAINE

Generation type	Capacity (MW)	Share (%)
Nuclear	13 835	25.95
Thermal (coal)	27 272	51.16
Cogeneration and other thermal	6 429.8	12.05
Hydro	5 465	10.26
Solar	187.5	0.35
Wind	121.1	0.23

TABLE 3.52. ELECTRICITY GENERATION STRUCTURE IN UKRAINE

Generation type	2010		2011		2012	
	TW·h	%	TW·h	%	TW·h	%
Nuclear	89.2	47	90.2	46	90.1	45
Thermal (coal)	86.5	46	93.6	48	97.1	49
Hydro	13.2	7	10.9	6	11.0	6
Total	188.8	100	194.9	100	198.9	100

Natural gas application for commercial generation is restricted by its limited reserves and considerable increase of import prices. Taking into account that gas fired power plants are the most suitable for responding to the peak loads, capacity factor is assumed to be about 32% (gas fired power plants are supposed to be highly manoeuvrable facilities, capable to respond to the peak loads). The model considers the following economic parameters:

— Capital construction costs are US $1300/kW.
— Construction period is three years.
— Fixed costs are about US $20/kW of installed capacity per year.
— Variable costs are about US $15/kW·h of generated electricity. The gas price is about US $350/kW·year (corresponds to the purchase price US $400/thousand m^3).

The energy potential of large rivers makes up 7.0 million t of standard fuel per year and is almost exhausted. The energy potential of small rivers is low and comprises 1.4 million t of standard fuel per year and cannot be considered as a significant factor for baseload generation. Hydropower plants have high energy potential in regulating peak loads and when it is necessary to reimburse the collapse of energy consumption. The main economic parameters of hydropower used in the model are listed below:

— Capacity factor is about 25%.
— Capital construction costs are US $2200/kW.
— Construction period is about 10 years.
— Fixed costs are about US $14/kW of installed capacity per year.
— Variable costs are about US $2.4/kW·h of generated electricity.

The following parameters of wind power are used in the model of energy system in Ukraine:

— Capacity factor is 26%.
— Capital construction costs are US $1900/kW.
— Construction period is one year.
— Fixed costs are about US $31/kW of installed capacity per year.

The following parameters of hydropower used in the model include:

— Capacity factor is 25%.
— Capital construction costs are US $2200/kW.
— Construction period is ten years.
— Variable costs are about US $2.4/kW·h of generated electricity.

The following parameters of solar energy are used in the model of energy system in Ukraine:

— Capacity factor is 16%.
— Capital construction costs are US $5000/kW.
— Construction period is one year.
— Fixed costs are about US $15/kW of installed capacity per year.

The major contributors in national electricity generation are the nuclear power plants (45–47%) and the fossil fuel burning power plants (43–49%); the hydropower plants share in total electricity generation is about 6–7%.

3.3.13.4. Summary presentation and analysis of the results

(a) Summary presentation

The study considered two scenarios of fast reactor implementation in Ukrainian nuclear fuel cycle: (i) construction of fast reactors after 2050; and (ii) substitution of LWRs by fast reactors after 2030. Operation of thermal and fast reactors (with MOX fuel for fast reactors) and CANDU reactors with reprocessed uranium is under consideration. This would involve LWR spent fuel reprocessing and fast reactor fuel fabrication for use in the Ukrainian fast reactors, and for reprocessed uranium fuel fabrication to be used in the Ukrainian HWRs. A centralized spent fuel dry storage facility is supposed to be commissioned in 2015 (according to the Energy Strategy of Ukraine, 2013).

(i) Construction of fast reactors after 2050

This configuration considers the commissioning of reactors of all types: LWR with UOX and MOX fuel; HWR with reprocessed uranium fuel; and fast reactors with MOX fuel. The model considers the possibility of LWR spent fuel disposal. The electricity generation structure and generation share with closed nuclear fuel cycle options are shown in Figs 3.231 and 3.232, respectively. The total installed nuclear capacity and the schedule of new capacities commissioning are presented in Figs 3.233 and 3.234. The spent fuel accumulation and accumulation of products derived from reprocessing are presented in Figs 3.235 and 3.236, in terms of accumulated volumes for extracted plutonium, minor actinides and fission products. The exhaustion of natural uranium resources is presented in Fig. 3.237.

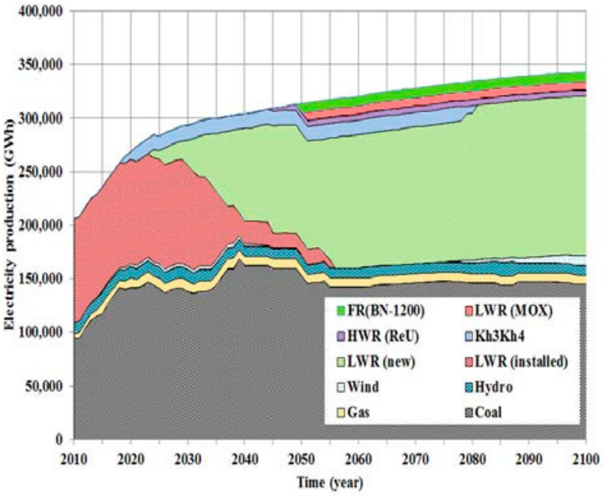


FIG. 3.231. Electricity generation structure.

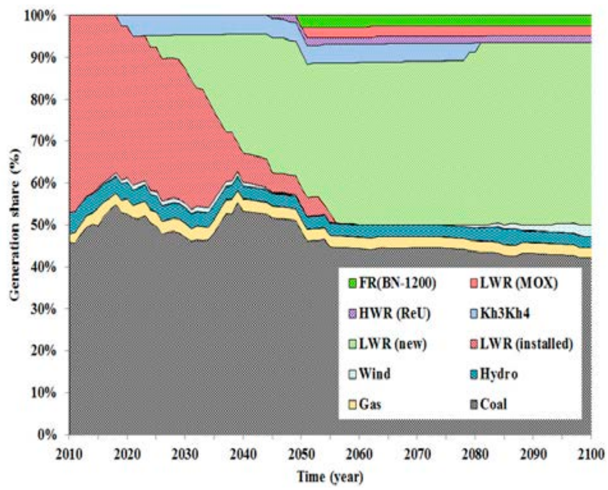


FIG. 3.232. Generation share.

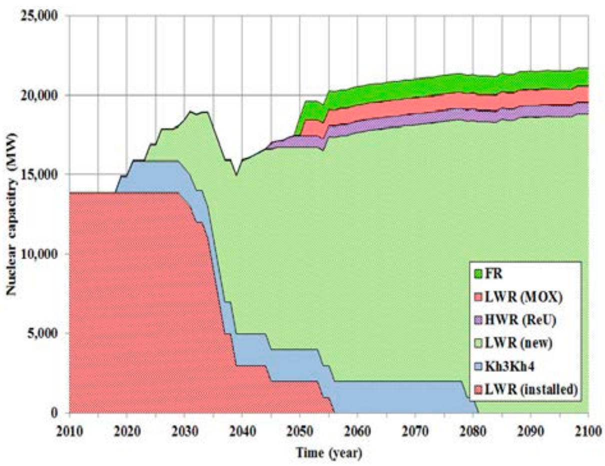


FIG. 3.233. Total installed capacities.

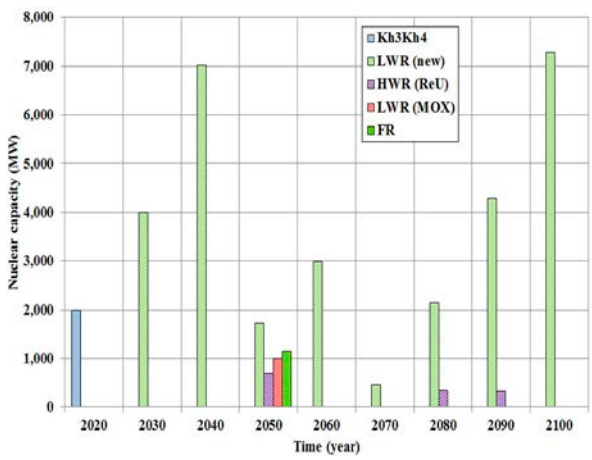


FIG. 3.234. Schedule of new capacities commissioning.

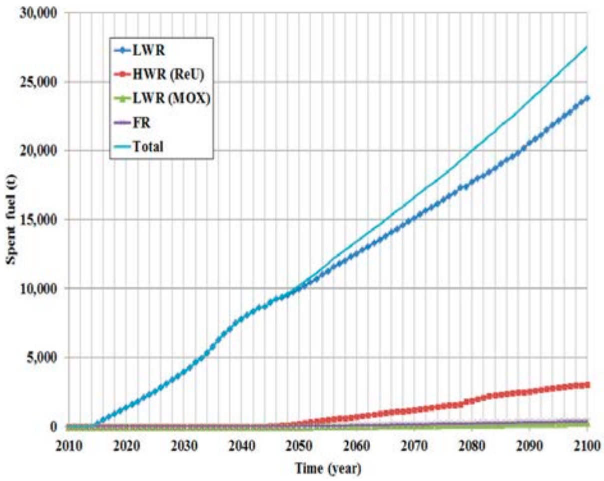


FIG. 3.235. Spent fuel accumulation.

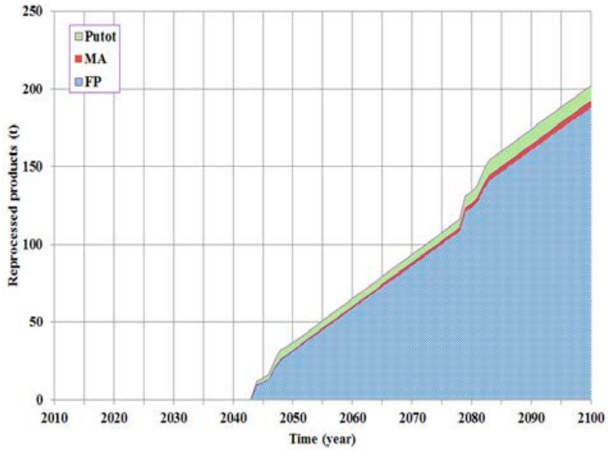


FIG. 3.236. Accumulation of products derived from reprocessing.

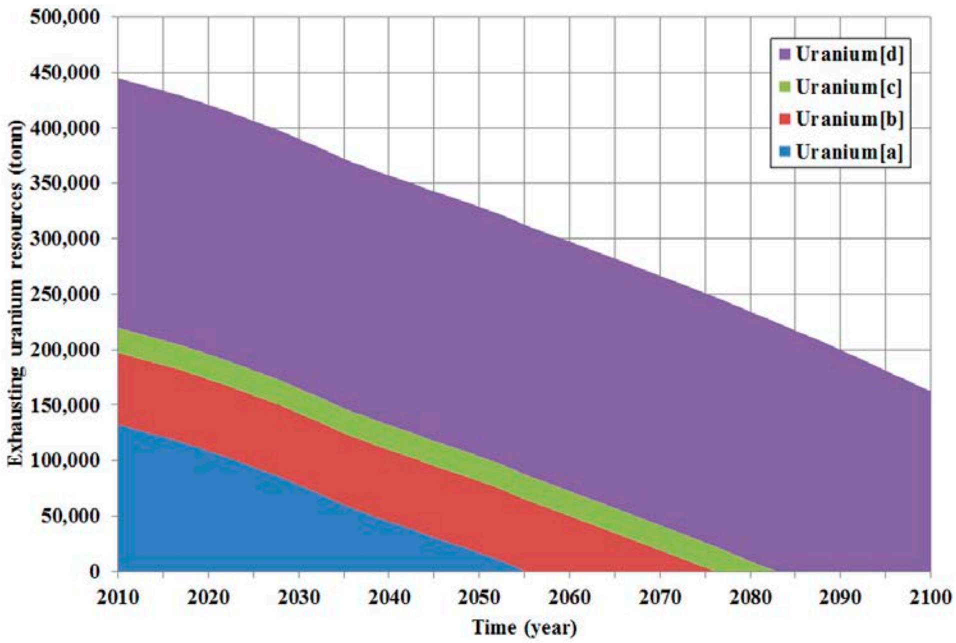


FIG. 3.237. Residual natural uranium resources: price categories of uranium reserves (a) US $100/kg, (b) US $120/kg, (c) US $150/kg and (d) US $260/kg.

(ii) Substitution of light water reactors by fast reactors after 2030

This section presents a capability assessment of fast reactors large scale deployment in a nuclear fuel cycle with multi-recycling of plutonium. LWRs replacement by fast reactors and spent fuel reprocessing are considered as a service. The commissioning of the centralized spent nuclear fuel dry storage facility is planned for 2015. Its capacity comprises 5650 t HM. Once it is full, an additional storage facility with the capacity of 2000 t HM will be commissioned. By 2030, five LWRs will be commissioned; after that only fast reactors will be commissioned.

LWR construction costs are US $5000/kW and for fast reactors US $6000/kW are needed. LWR spent fuel reprocessing costs are US $2000/kg, fast reactor spent fuel reprocessing costs are US $2400/kW, and reprocessing is considered as a service. The electricity generation structure and generation share with closed fuel cycle options and multi-recycling options are shown in Figs 3.238 and 3.239. The total installed nuclear capacity and the schedule of new capacities commissioning are presented in Figs 3.240 and 3.241. Accumulation of spent fuel and products derived from reprocessing are presented in Figs 3.242 and 3.243, with accumulated volumes of extracted

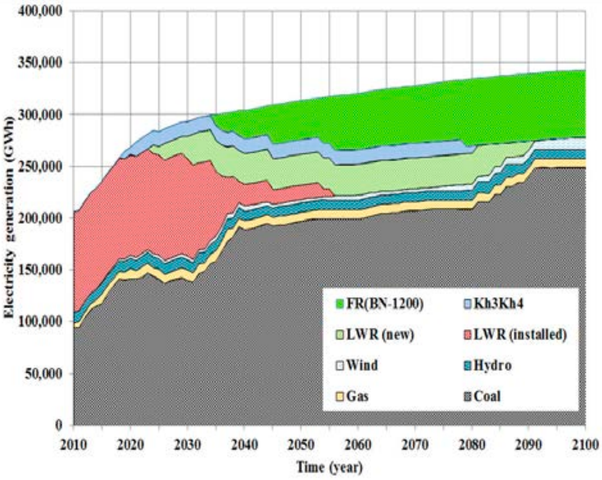


FIG. 3.238. Electricity generation structure.

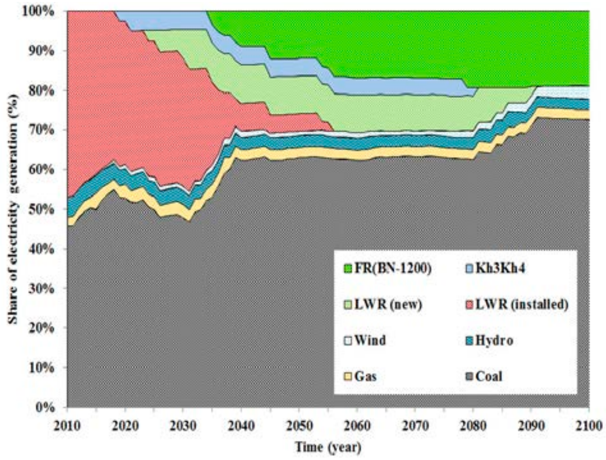


FIG. 3.239. Share of electricity generation.

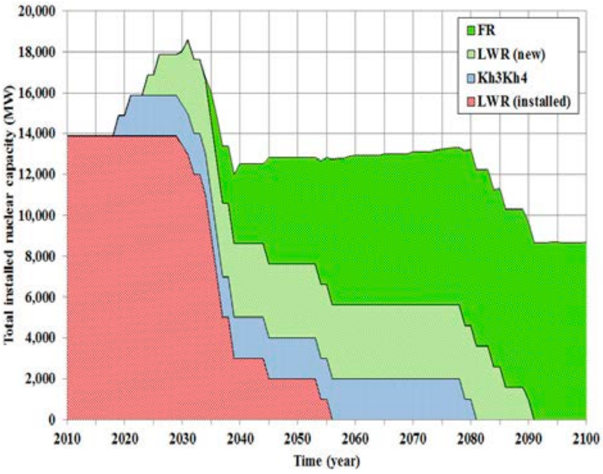


FIG. 3.240. Total installed capacities.

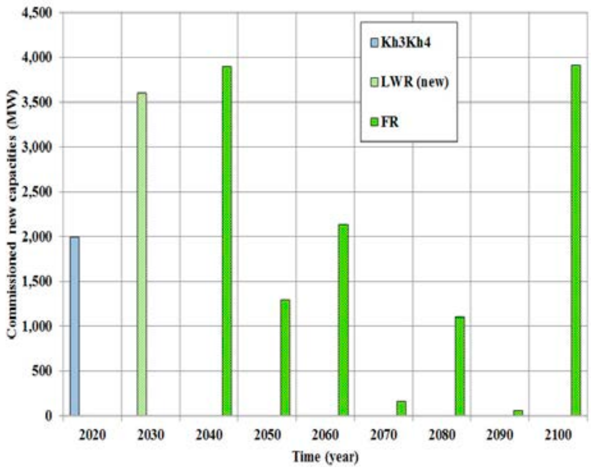


FIG. 3.241. Schedule of new capacities commissioning.

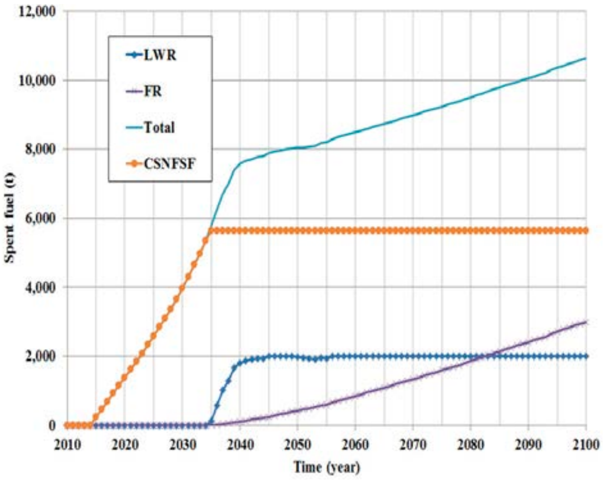


FIG. 3.242. Spent fuel accumulation.

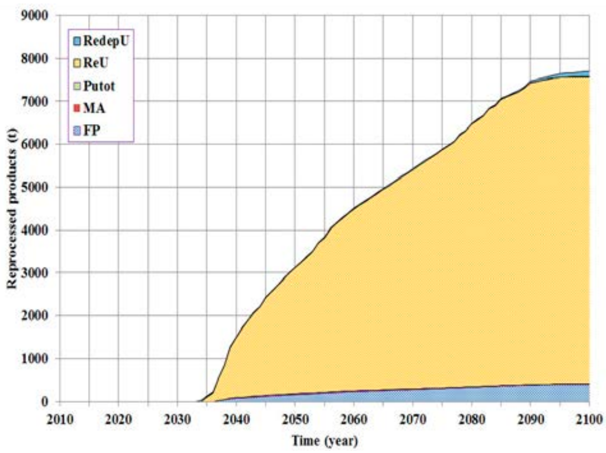


FIG. 3.243. Accumulation of products derived from reprocessing.

plutonium, minor actinides and fission products. Reprocessed depleted uranium is regenerated from fast reactor spent fuel; reprocessed uranium is regenerated from LWR spent fuel. An assessment of extracted plutonium, minor actinides and fission products from reprocessing is presented in Fig. 3.244. Natural uranium resources exhaustion is presented in Fig. 3.245.

(b) Analysis of the results

(i) Construction of fast reactors after 2050

When considering construction of fast reactors after 2050, the modelling demonstrates that there are only LWRs in the system if the selected initial conditions and assumptions are considered, due to the low capital costs of their commissioning, low cost of UOX fuel fabrication, high costs of spent fuel reprocessing services and considerable reserves of natural uranium. In case of an open nuclear fuel cycle, the dynamics of spent fuel shipments up to 2100 is presented in Fig. 3.246 (the colours of line correspond to construction costs of US $3000/kW, US $5000/kW and US $5500/kW).

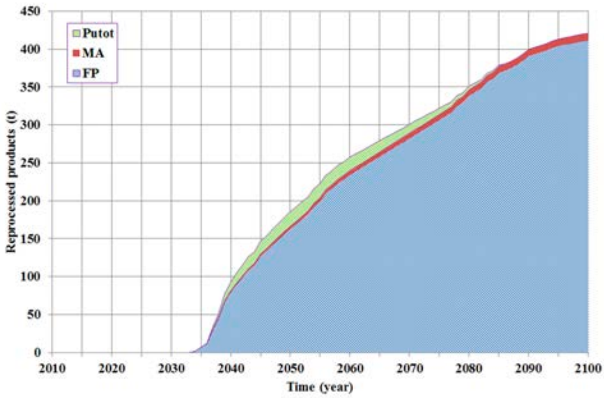


FIG. 3.244. Accumulation of products derived from reprocessing: specified accumulated volumes of extracted plutonium, minor actinides and fission products.

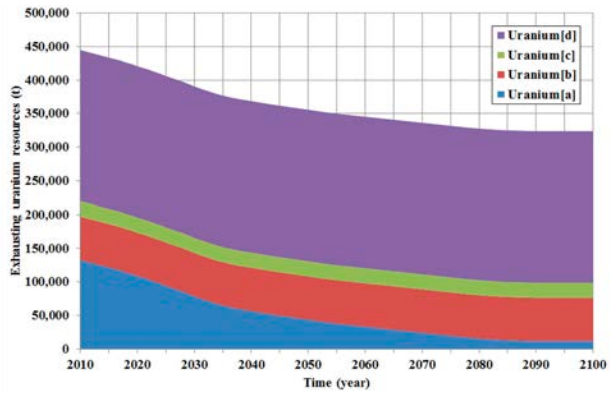


FIG. 3.245. Nature uranium resources exhaustion.

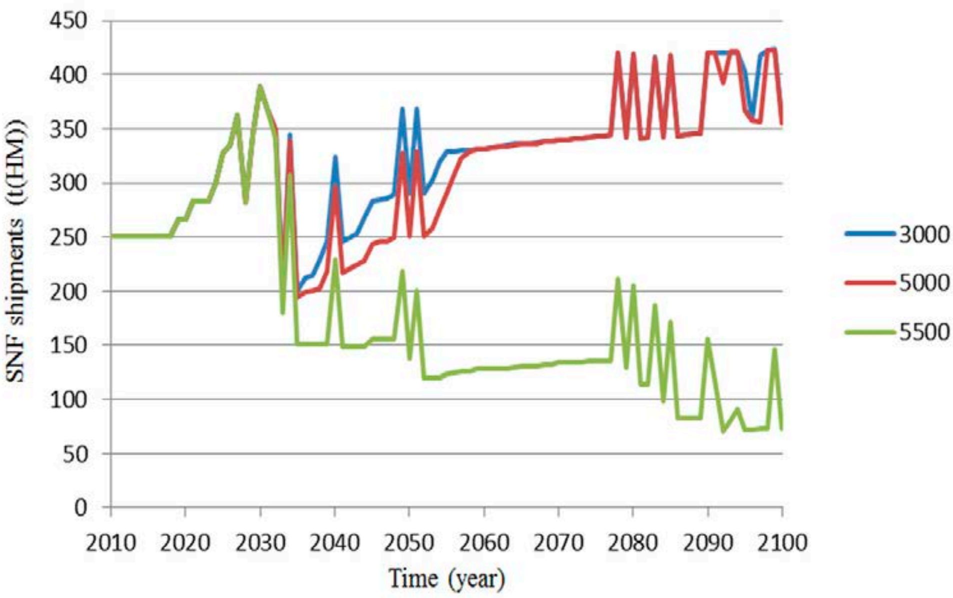


FIG. 3.246. The dynamics of spent fuel shipments until 2100.

To assess the potential impact of MOX fuel and fast reactor deployment on the system, an obligatory commissioning of one LWR with MOX fuel and one fast reactor is considered in 2050. An LWR with UOX fuel remains the main reactor type in the system. Considering the model requirement that refers to the necessity of LWR spent fuel reprocessing for MOX fuel fabrication to be used in this LWR, the nuclear fuel cycle is automatically complemented with HWR with reprocessed uranium fuel that can be commissioned not earlier than 2030.

The modelling results show the reduction of the nuclear share down to 40–43% from the existing level as a result of decommissioning of actual operating reactors and the slow commissioning rate of replacement reactors, as considered in the updated energy strategy of fuel and energy sector development in Ukraine until 2030 (see Figs 3.231 and 3.232). This result complies with the obtained results for a once through fuel cycle and a partially closed fuel cycle, confirming the correctness of the model.

A condition to maintain the 50% nuclear share in the Ukrainian energy system requires the commissioning of a significant amount of nuclear capacities in 2030–2040, which will impose a significant financial burden on the country; this cannot be considered as a realistic scenario. Total installed capacity of new LWRs will comprise 7 GW(e) in this period.

The operation of reactors with MOX fuel and of one fast reactor with plutonium fuel in 2050 requires LWR spent fuel to be reprocessed and one HWR with the reprocessed uranium fuel be deployed over the indicated period. It should be noted that there are no limitations regarding the number of LWRs with MOX fuel and fast reactors in the model of this study. However, taking into account the technical and economical parameters of a reactor and the fuel cycle mentioned in Annex XIII, the commissioning of these reactors is performed at the minimal level. This is related to the absence of restrictions regarding the amount of accumulated LWR spent fuel, natural uranium prices and its reserves.

The results with regard to accumulation of spent fuel and reprocessing products are similar with the option based on a partially closed fuel cycle due to the low share of fast reactors in the fuel cycle. The amount of accumulated spent fuel will total up to 28 000 t HM, including 4000 t HM of HWR spent fuel, and 24 000 t HM of LWR spent fuel. The total amount of accumulated MOX spent fuel and fast reactor spent fuel will be less than 1000 t HM by 2100 (see Fig. 3.235). The small amount of reprocessed LWR spent fuel corresponds to the small amount of obtained reprocessing products (up to 200 t HM). The amount of extracted plutonium is about 20 t HM.

The discounted cost of electricity for this type of fuel cycle based on one LWR with MOX fuel, one fast reactor and one HWR with reprocessed uranium fuel, at zero cost, makes up US \$14.08/MW·h that complies with the cost in a once through fuel cycle. Natural uranium reserves of 447 000 t HM will be sufficient until 2150, which complies with the guidelines for a partially closed fuel cycle.

(ii) Substitution of light water reactors by fast reactors after 2030

The modelling demonstrates that nuclear share in electricity generation will reduce down to 20% by 2100 (see Figs 3.231 and 3.232). This relates to the high cost of closed fuel cycle technologies. Spent fuel reprocessing will start when storage facilities are filled (approximately in 2035). The total installed capacity of new reactors will comprise 4 GW in 2030–2040. In addition, up to 4 GW will be commissioned in 2040–2080 (see Fig. 3.241).

Fresh fuel for fast reactors is fabricated from plutonium extraction and reprocessing of LWR spent fuel. LWR spent fuel reprocessing will be stopped when the last LWR is decommissioned (in 2090). Termination of LWR spent fuel reprocessing can also be seen on the graph showing the accumulation of regenerated uranium (see Fig. 3.243): regenerated uranium produced after LWR spent fuel reprocessing is accumulated only till 2090, after that the accumulation of regenerated uranium produced after fast reactor spent fuel reprocessing will start. Fast reactor spent fuel reprocessing will start after 2090 since it contains more plutonium.

The model considers fast reactor spent fuel accumulation till 2100. Total amount of accumulated spent fuel will comprise 11 000 t HM, including 2000 t HM of LWR spent fuel and 3000 t HM of fast reactor spent fuel. Owing to the considerable amount of spent fuel subject to reprocessing, the total amount of reprocessing products will comprise 8000 t HM, including 7000 t HM of regenerated uranium.

This option of fuel cycle does not consider plutonium accumulation. All plutonium will be used till 2100. It may be considered as a significant benefit of this cycle involving spent fuel reprocessing. The economy of this fuel cycle should be studied separately. However, in case of significant reduction of nuclear reactors in the system by 2100 and utilization of plutonium extracted from fast reactor spent fuel, the discounted cost of electricity generation will be US \$12/MW·h, which is much lower than in case of the once through fuel cycle.

The depletion of natural uranium reserves during the period of study for this type of fuel cycle is presented in Fig. 3.245. No reduction of uranium reserves is expected, neither till 2100 nor in the future. By 2100, uranium reserves will be up to 340 000 t, regardless of further reductions in the rate of uranium reserve depletion. This confirms the sustainability of the energy system in accordance with the IAEA sustainability concept.

3.3.13.5. Conclusions

In the framework of activities performed under the IAEA collaborative project SYNERGIES (Task 1), two options for developing the NES in Ukraine were analysed: a closed fuel cycle based on fast reactors which will be constructed after 2050: and substitution of LWRs by fast reactors after 2030. The commissioning of fast reactors is deferred for a later term due to the availability of uranium resources in large amounts, the high cost of fast reactors and high reprocessing costs.

Considering the restrictions and input data used in this study, the closed fuel cycle based on fast reactors in Ukraine is found to be economically unattractive on account of the following:

— Availability of large uranium reserves;
— High cost of fast reactor construction;
— High cost of spent fuel reprocessing;
— High cost of fresh and MOX fuel fabrication for fast reactors.

The share of nuclear power plants in power generation is primarily increased by HWRs using regenerated uranium; this requires separate studies to be performed. When considering the economics of a fuel cycle, making use of significant amounts of regenerated uranium at cost could allow an increase in the nuclear power plant share up to 50%. In addition, a more feasible scenario would involve reducing of the commissioning rate down to 4.5 GW for new reactor capacities in 2030–2040.

Meeting the limitations on accumulation of spent fuel requires the reprocessing of spent fuel to start in 2045, which is also a prerequisite for commissioning fast reactors, LWRs on MOX fuel (plutonium utilization) and HWRs on regenerated uranium by 2050. It would be reasonable to require reprocessing of fast reactor spent fuel as it will have a high content of fissile materials. Closing the fuel cycle with a fast reactor programme will significantly decrease the amount of spent fuel accumulation. The transition to a closed fuel cycle could be preconditioned by limitations on capacities for spent fuel disposal (limited storage capacities), accumulation of spent fuel assemblies and decreasing of uranium reserves.

The input data on cost (price range) of fast reactors and associated reprocessing of their spent fuel should be discussed with manufacturers and services suppliers. The modelling results depend significantly on the price parameters. In addition, the sensitivity analysis should be performed depending on a cost of technologies and services.

To provide one fast reactor with fuel requires reprocessing spent fuel from ten LWRs. However, reprocessing of spent fuel increases the cost of the fuel cycle. Based on the analysis of the results, it is clear that reprocessing of spent fuel from fast reactors (instead of spent fuel from LWRs) is feasible due to the much higher content of fissile material. The LCOE is US $14.08/MW·h for the single fast reactor implementation on the fuel cycle, and US $12/MW·h for the case with substitution of LWRs with fast reactors after 2030. The capital cost of reactors which were built before 2012 has not been considered. This analysis suggests that the most sustainable approach would involve developing international cooperation in the fuel cycle back end, specifically for the reprocessing of spent fuel from LWRs and fabrication of MOX and reprocessed uranium fuel.

3.4. SCENARIOS OF TRANSITION TO TH/^{233}U FUEL CYCLE AND SCENARIOS WITH ALTERNATIVE U/PU/TH FUEL CYCLES (SCENARIO FAMILY D)

3.4.1. Evaluation of a scenario of transition to Th/^{233}U fuel cycle

3.4.1.1. Introduction

Task 1 of the INPRO SYNERGIES project focuses on assessing scenarios involving use of PHWR, LWR and fast reactor technologies using uranium and/or plutonium as main fissile content of the fuel. Its scope is also extended to analyse the scenario of using thorium based fuel that may be introduced in the medium term time frame, from 2030 to 2050. Among various scenario storylines, Scenario family D envisages transition to a thorium/^{233}U fuel cycle via use of uranium/plutonium in thermal and fast reactors. While results of a study considering the storyline of Scenario family D have been published [3.12], a parametric study was carried out to assess the effect of the availability of fast reactor technologies using metallic fuel in transition to a thorium/^{233}U fuel cycle. The complete case study can be found in Annex XVI on the CD-ROM accompanying this publication.

3.4.1.2. Objective and problem formulation

(a) Description of the storyline

As stated, the storyline for this study is similar to the India's three stage nuclear power programme. The three stage Indian nuclear power programme is aimed at efficient utilization of limited natural uranium and extensive thorium reserves. The first stage comprises of use of uranium based fuel for power generation primarily in PHWRs. The power programme is expanded in the second stage through fast breeder reactors (FBRs) using plutonium based fuel, with depleted/reprocessed uranium in the blanket and with a high breeding ratio, which serves to increase the fissile inventory available for breeding ^{233}U from thorium. Thorium is gradually introduced into the FBR blanket to breed ^{233}U. The third stage would use this ^{233}U along with thorium in a self-sustainable manner (see Fig. 3.247). It should be noted that the current study is only a case study and should neither be considered as a commitment of installation nor any statement of targets for India.

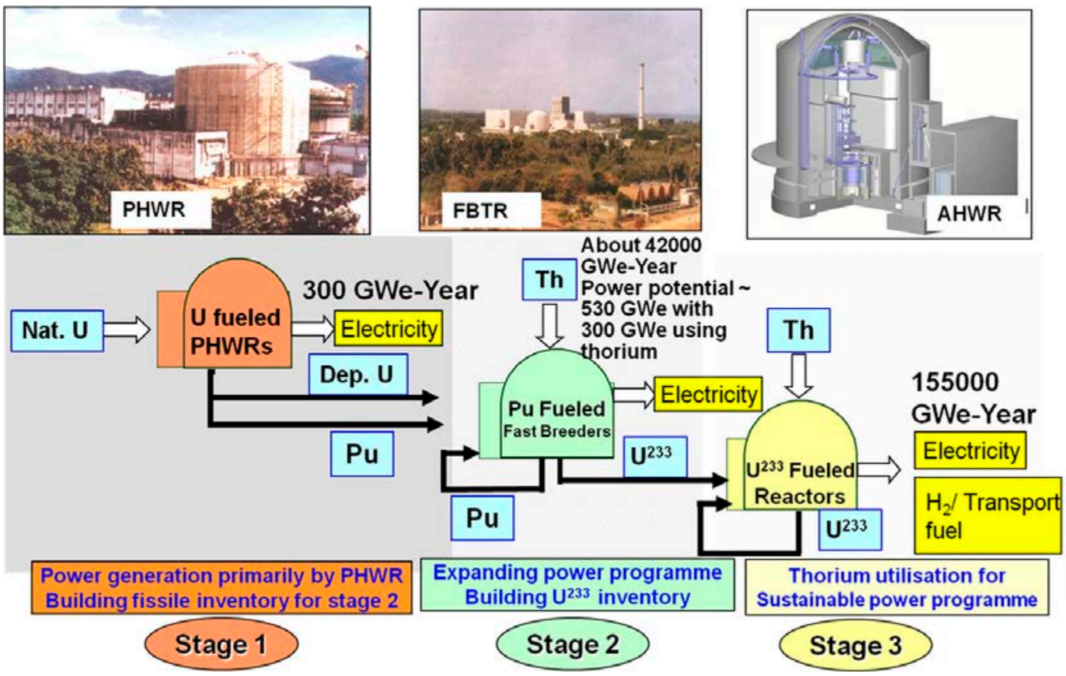


FIG. 3.247. Overview of the Indian three stage nuclear programme.

(b) Objective of the study

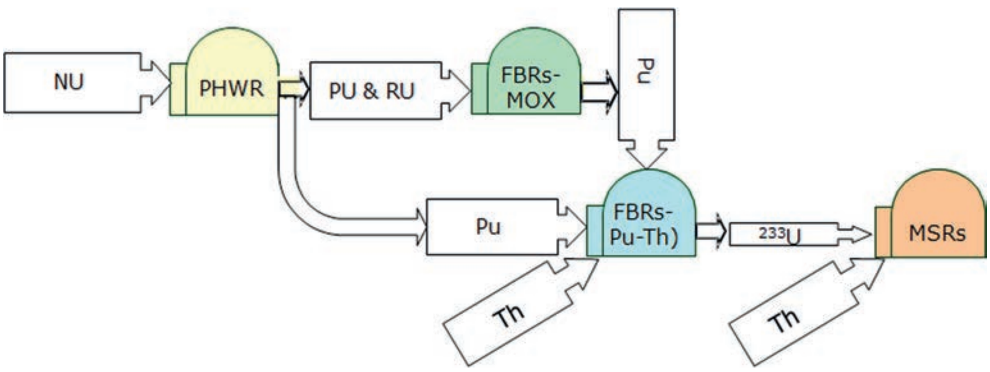
It has already been established that the time of thorium introduction is very important in achieving and sustaining the target power level. Use of thorium requires sufficient building up of fissile inventory. As use of metallic fuel in FBRs results in higher breeding ratio compared to use of oxide fuel, the availability of technology for using metallic fuel in FBRs, along with its associated fuel cycle, is essential for building up the necessary fissile inventory at faster rate. This eventually plays a vital role in transiting to a thorium/^{233}U fuel cycle. The effect of availability of this technology on time of transition to the third stage using the thorium/^{233}U fuel cycle has been assessed in this parametric study.

3.4.1.3. Assumptions, methods, codes and input data used

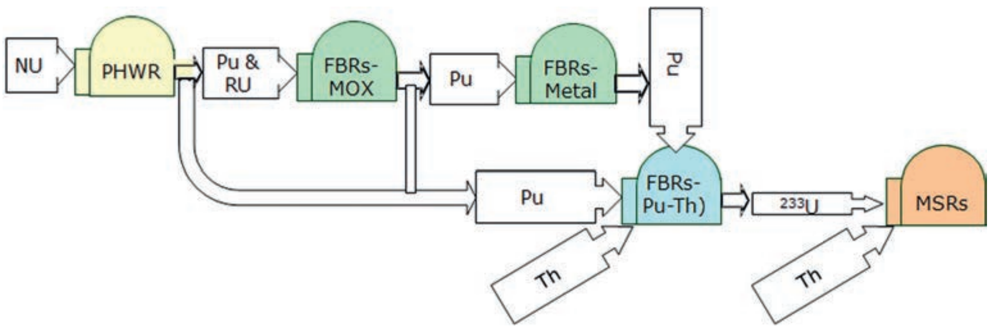
(a) Description of case study scenarios

Figure 3.248 explains the two storylines of the different scenarios, Cases A and B. Case B envisages the availability of technology for using metallic fuel in FBRs. The parameters considered for this case study are listed in Table 3.53.

Material requirements reported in Ref. [3.103] for fast reactor systems have been considered for the study. The plutonium–uranium metal fuelled FBRs have blankets containing thorium metal, with an overall breeding ratio of 1.58. The plutonium–thorium metal fuelled FBRs have thorium metal in the fertile blanket, with an overall breeding ratio of 1.3. The target power level has been assumed to be 1000 GW(e) for both cases. It is assumed that the primary factor limiting the installation and commissioning of nuclear power plants is the need to ensure the lifetime availability of nuclear material. Thus, any limitation arising out of availability of non-fissile or non-fertile materials are not taken into account, which includes, among others, fuel clad material, structural material and fabrication infrastructure.



(a) Case A



(b) Case B

FIG. 3.248. Nuclear reactor chain configuration.

TABLE 3.53. PARAMETERS FOR THE STUDY

Parameters	Case A	Case B
Material availability		
U	~60 000 t	
Th	~225 000 t	
Preferential order of reactor installation	PHWRs (nat. U) FBRs (Pu/U MOX) FBRs (Pu/Th metal) not before 2041 MSRs not before 2041	PHWRs (nat. U) FBRs (Pu/U MOX) FBRs (Pu/U metal) not before 2021 FBRs (Pu/Th) not before 2041 MSRs not before 2041
Time duration for return of spent fuel as refabricated fuel	1 year	
Material losses	1%	

Note: FBR — fast breeder reactor; MOX — mixed oxide; MSR — molten salt reactor; PHWR — pressurized heavy water reactor.

(b) Tool used for the study: Tool for Energy Planning Studies

The Tool for Energy Planning Studies (TEPS) was designed for energy planning studies relevant for electricity producing nuclear reactor systems. The current version of TEPS can handle up to 20 reactor types and 20 material types, and systematic upgrading is in progress to accommodate more. Within a typical NES, there is no fundamental limit on the number of reactors that can be installed.

The input to the code consists of metadata on overall information, such as number of reactor types involved in the analysis, number of materials to be tracked, the target energy demand curve, material availability information, the user defined reactor deployment priority and prior installation history (so as to be able to start an analysis from some well defined point in time). The code additionally requires information on material requirements (annualized flows in the current version) for each of the nuclear reactor types that are going to be employed in the analysis. These flows contain, typically, the initial core requirements, annual reload requirements, annual discharges from the reactor, and the quantity that will be discharged at the time of decommissioning of the reactor, as well as the rated reactor power and lifetime load factor, the typical time for the reusable components from the spent fuel bay to the refabrication of fresh fuel, reprocessing losses, construction period and reactor lifetime to be provided. The TEPS code utilizes the information to calculate the material flows needed to achieve the target demand curve. In the event the target demand curve is non-commensurate with the material availability information provided, TEPS will automatically adjust and calculate the maximum installations possible.

Fundamentally, TEPS is an optimization code that tries to maximize reactor installations subject to material and priority constraints. The material flows provided as output by TEPS are completely user specific and non-radiological (decay of radioisotopes is not considered). The user specificity is useful when, for example, a user is interested in obtaining the minor actinide load arising out of an NES; a user may track such minor actinides that are essential to analysis. Similarly, users analysing the requirements for infrastructural materials may choose to monitor the amount of steel needed for an NES. The material flows that need to be mandatorily tracked are the fissile and fertile materials, such as ^{233}U, ^{235}U, ^{238}U, plutonium and thorium.

An interesting feature that is employed in TEPS is to account for lifetime requirements of material for a given reactor type. To consider this, TEPS employs a forward looking calculation that inhibits reactor installations that would result in negativity of material flow at some future point of time. It should be emphasized that the lifetime requirement of a reactor is not allocated at the outset, but merely factored in as a constraint to the optimization problem. Additional constraints can be added to the code using the construction period limits by formulating either a cap on the maximum reactors that can be constructed in the period or on the total number of reactors of any one kind.

TEPS has been benchmarked with the IAEA Nuclear Fuel Cycle Simulation System (NFCSS) and was extensively employed for scenario analysis in INPRO GAINS.

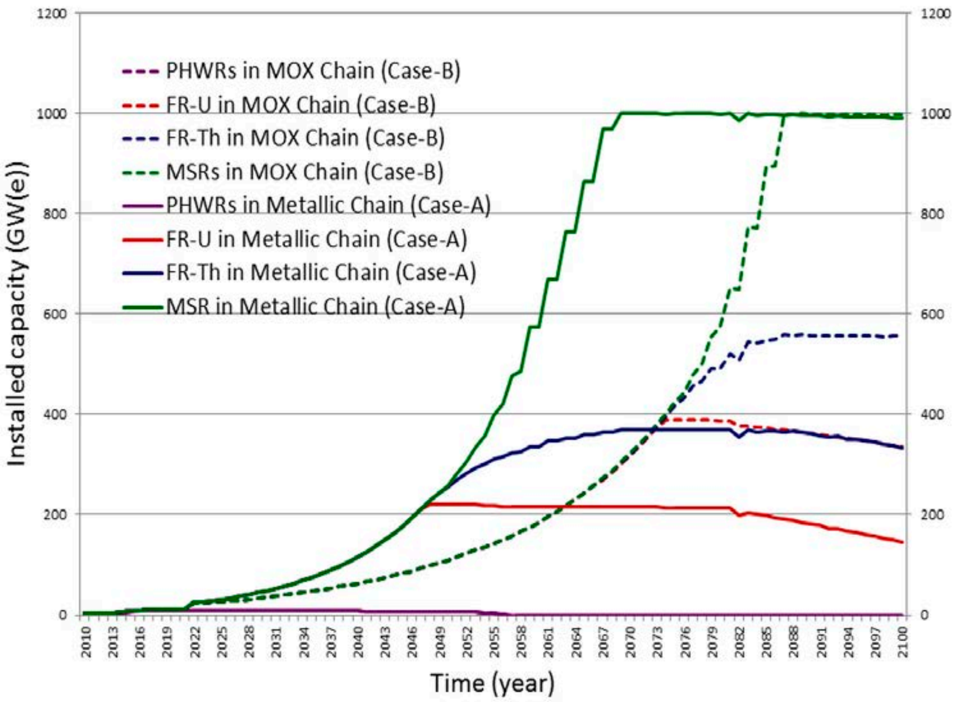


FIG. 3.249. Calculated installed capacity with time.

3.4.1.4. Summary presentation of the results and analysis of the results

For the input parameters given in Table 3.53, TEPS delivers the possible installed capacity for various reactor types with time. Figure 3.249 shows installed capacities of various reactor systems with time. It shows that in the absence of availability of the technology for using metallic fuel in FBRs, the transition of introducing thorium in blankets of fast reactors is delayed by 14 years. For Case A, this transition is possible in 2062; while for Case B, it is possible in 2048. Moreover, there is an 18 year delay in achieving the target power level of 1000 GW(e). The year in which target power level could be achieved is 2087 and 2069 for Cases A and B, respectively.

3.4.1.5. Conclusions

The indicative assessment for Scenario family D of SYNERGIES Task 1 (see Section 2.7.5) confirms that fast reactors using metallic fuel can have a significant role in advancing the time period for transition to deployment of Th/^{233}U based reactors. Furthermore, it is notable that the key indicators shortlisted as a part of the SYNERGIES programme may not be able to compare these scenarios, since the time factors which are essential to these results are not considered.

3.4.2. Summary of INPRO studies on global scenarios with introduction of Th

3.4.2.1. Introduction

INPRO carried out several assessment studies at global, regional and national levels to determine the potential of NESs to become a sustainable energy supply option in the 21st century. Special attention was paid to consideration of thorium based nuclear fuel cycle studies considering the potential role of thorium in supplementing the uranium–plutonium fuel cycle [3.12, 3.25, 3.52]. Fuel cycles based on ^{232}Th may provide an opportunity to use vast deposits of this nuclear material to supply future large scale deployment of NESs and enhance the sustainability of nuclear power. This section comprises the INPRO scenario studies based on a wide scope of reactor options designed for thorium based fuel use. The studies belong to SYNERGIES Task 2, on evaluation of additional options for NES with thermal and fast reactors, and provides economical assessment and examining the potential of thorium based fuel cycles to support future large scale deployment of NESs by enhancing the availability of nuclear materials.

3.4.2.2. Objective and problem formulation

The overall objective of the studies was to examine the potential of thorium based fuel cycles to enhance the sustainability of nuclear power. More specifically, the following issues were considered:

— Potential for reduction in ^{235}U enrichment requirements and natural uranium requirements in the case of thorium utilization;
— Reduction of long lived radioactive waste inventories by diminishing the production of plutonium and minor actinides;
— Advantages from increasing global fissile resources by breeding ^{233}U from thorium;
— Estimation of fabrication and reprocessing capacities necessary for commercial utilization of thorium fuels and fuel cycles.

Three variants (splitting in few options) of thorium fuel introduction were examined in the scenario studies:

— Once through fuel cycle based on thermal reactors utilizing thorium without spent fuel reprocessing;
— Closed fuel cycle based on thermal reactors utilizing thorium and/or ^{233}U with spent fuel reprocessing and ^{233}U (as well as plutonium) recycling;
— Closed fuel cycle based on thermal and fast reactors utilizing thorium and/or ^{233}U with spent fuel reprocessing and recycling of ^{233}U and plutonium.

In total, eight NESs consisting of combinations of ten types of thermal reactors were considered in once through and closed fuel cycles. Seven NESs with combinations of 12 types of thermal and fast reactors with closed fuel cycles were considered closed fuel cycles (see Table 3.54).

TABLE 3.54. TYPES OF REACTORS BASED ON UOX–MOX FUEL AND ON THORIUM FUEL

Type of reactor based on	Reactor index	Fuel type
UOX–MOX fuel		
1	HWR	Nat. U
2	LWR	UOX
3	ALWR	UOX
4	LWR_M	MOX
5	FR (BR~1)	MOX, DU
6	FR12 (BR~1.2)	MOX, DU
Th fuel		UO_2, Th
7	LWR0	Pu, Th
8	LWR1	Pu, U3, DU
9	LWR2	Th, U3
10	LWR3	Pu, Th
11	HWR1	Pu, U3, Th
12	HWR2	Pu, U3, Th
13	HWR3	U3, Th
14	HTR	Pu, DU, Th in blankets
15	FR_Th	

Note: ALWR — advanced light water reactor; BR — breeding ratio; DU — depleted uranium; FR — fast reactor; HTR — high temperature reactor; HWR — heavy water reactor; LWR — light water reactor; MOX — mixed oxide; MSR — molten salt reactor; UOX — uranium oxide.

3.4.2.3. Assumptions, methods, codes and input data used

The methods, major assumptions and boundary conditions for NESs, as well as data for thermal and fast nuclear power plants for uranium–plutonium fuel cycles used in the studies, were based on the analytical framework for assessing transition scenarios to future sustainable NESs developed in the GAINS collaborative project (see Tables 3.55 and 3.56) [3.52]. Typical characteristics were used for existing LWRs and HWRs. Improved technical characteristics (more burnup and enrichment) were used for AHWRs and ALWRs.

Member States participating in the studies provided data on the reactors utilizing thorium/^{233}U fuel (see Tables 3.56 and 3.57) in the scenario simulation. A fast reactor with a break-even breeding ratio (i.e. close to 1.0)

TABLE 3.55. DATA ON THERMAL REACTORS IN URANIUM/PLUTONIUM FUEL CYCLES

Item	LWR	ALWR	HWR
Reactor net electric output (MW)	1000	1500	600
Reactor thermal output (MW)	3030	4410	2000
Av. load factor (%)	80	80	80
Plant lifetime (years)	40	60	40
Av. discharge burnup (MW·d/t)	45 000	60 000	7000
Fuel residence time (EFPD)	1168	1760	292
Fresh fuel U enrichment (%)	4	4.9	0.711
Cooling time (years)	5	5	5

Note: ALWR — advanced light water reactor; EFPD — effective full power days; HWR — heavy water reactor; LWR — light water reactor.

TABLE 3.56. DATA ON THERMAL REACTORS UTILIZING TH/^{233}U FUEL

	LWR0	LWR1	LWR2	HWR1	HWR2	HTR
Acronym	UOX_Th	Th_Pu	Pu_U3	Pu-Th	Pu-Th-U3	Th_U3
Reactor electric output (MW)	900	900	1000	668	668	270
Efficiency (electricity)	0.32	0.32	0.33	0.32	0.32	0.45
Av. load factor	0.8	0.8	0.8	0.95	0.95	1
Plant lifetime (years)	60	60	60	60	60	60
Av. discharge burnup (MW·d/t)	38.2	40.5	42.7	20.3	20	83
Construction time (years)	5	5	5	5	5	5
Fuel residence time (EFPD)	927	983	885	825	810	833
First fuel loading (t)	67	67	70.3	71.4	71.4	6
Pu content		0.074	0.024	0.038	0.011	—
Th content	0.76	0.913	—	0.096	0.915	0.92
U3 content	—	—	0.018	—	0.014	0.08

Note: EFPD — effective full power days; HTR — high temperature reactor; HWR — heavy water reactor; LWR — light water reactor; UOX — uranium oxide.

TABLE 3.57. DATA ON FAST REACTORS

Item	FR_Th	FR-MOX
Reactor electric output (MW)	880	870
Efficiency (electricity) (%)	42	42
Av. load factor (%)	85	85
Plant lifetime (years)	60	60
Average discharge burnup (MW·d/t)	72	65.9
Breeding ratio		1
Construction time (years)		5
Fuel residence time (EFPD)	441	Core: 420 Axial blanket: 420 Radial blanket: 490
First fuel loading (t)	12.5 33 (Th blanket)	Core: 12.6 Axial blanket: 5.5 Radial blanket: 6.2
Pu content (%)	0.218 Th (Th blanket)	Core: 22 Axial blanket: dep U Radial blanket: dep U

Note: dep U — depleted uranium; EFPD — effective full power days; FR — fast reactor; MOX — mixed oxide.

was considered. FR_Th is similar to the fast reactor but contains ^{232}Th in the blankets, where the breeding of ^{233}U takes place. More details on reactor and associated fuel cycle data can be found in Refs [3.12, 3.25, 3.52].

Two GAINS nuclear energy demand scenarios were selected for analysis. The high case scenario assumes generation of 1500 GW·year by the middle of the 21st century and 5000 GW·year by 2100. In the moderate case scenario, 1000 GW·year of world nuclear generation was assumed to be reached by the middle of the 21st century and 2500 GW·year by 2100. Another assumption that can be very important from the point of view of thorium introduction is the postulated share of heavy water moderated reactors. In most scenarios, this fraction is defined at the level of 6% of total capacity.

To analyse these scenarios, the world was divided into three non-geographical groups of countries, with different policies regarding the back end of the nuclear fuel cycle. The GAINS approach also implies several assumptions on reactor and fuel cycle features reported in Ref. [3.52].

Material flow calculations were performed with the tools MESSAGE and DESAE. Special models were created in the MESSAGE code for thorium fuel cycle introduction options. Calculations of scenarios featuring introduction of thorium and ^{233}U fuel in thermal reactors (LWRs and HWRs) were performed. DESAE is an interactive material flow analysis code for quantitative assessment of nuclear fuel cycle requirements, material balances and economics. The calculations included optimization of material flows and economic considerations. In some cases, the ORIGEN-S + Excel spreadsheet calculation was used for decay heat calculation. Economics analysis and assessment is based on INPRO methodology (see Appendix II). NEST, developed within INPRO, was used for the calculation of the LUEC of different reactors with different fuel cycles.

The study [3.12] compiled economic parameters reactors including LWRs, HWRs and fast reactors. The ^{233}U/Th fuelled reactors are assumed to have the same capital cost and cost of operation and maintenance as the similar type of uranium/plutonium reactors. The following indicators were calculated for the assessment of different NES options:

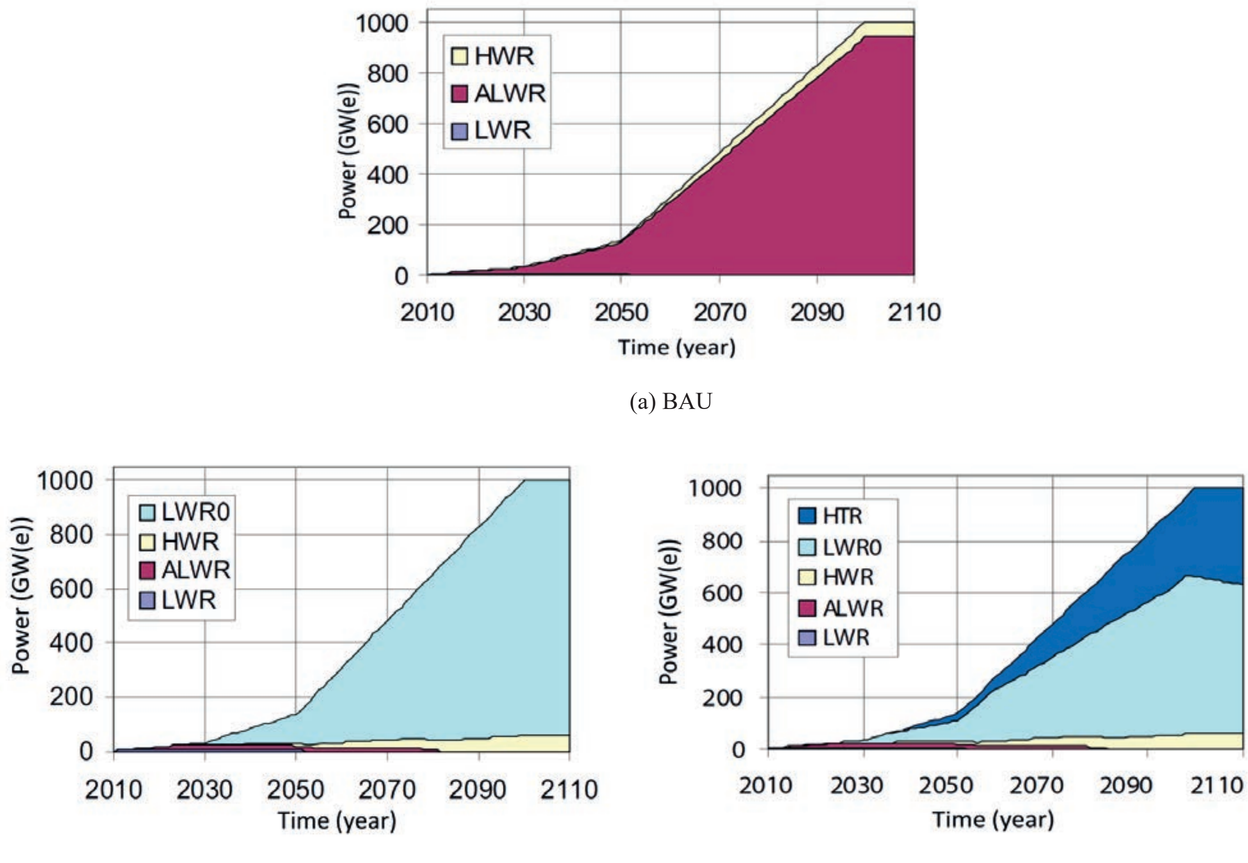
- — Nuclear electricity generation structure;
- — Cumulative natural uranium consumption;
- — Enrichment requirements;

— Fuel fabrication requirements;
— Reprocessing requirements;
— Spent fuel accumulation;
— Annual plutonium discharged/consumption;
— Annual minor actinide discharged, minor actinide accumulation;
— Annual ^{233}U discharged/consumption.

3.4.2.4. Summary presentation and analysis of the results

(a) General assumptions

Figure 3.250 addresses thorium introduction in the GAINS group of countries NG3 (countries without fast reactors in the 21st century) in the high demand scenario. Three options are compared (BAU, LWR0 and LWR0&HTR). The thorium based reactors under consideration are LWR0 using enriched UOX and thorium fuel, and HTR using ^{233}U and thorium fuel. BAU and LWR0 options are based on a once through fuel cycle without reprocessing of spent fuel. The LWR0 and HTR option is based on a closed fuel cycle with reprocessing of thorium spent fuel after its discharge from LWR0 and HTR. There is no incineration of civilian grade plutonium in these options. The maximum introduction of thorium option following the ^{233}U availability is considered, assuming the share of HWR is kept at 6% of the total nuclear power.



(a) BAU

(b) LWR0

(c) LWR0&HTR

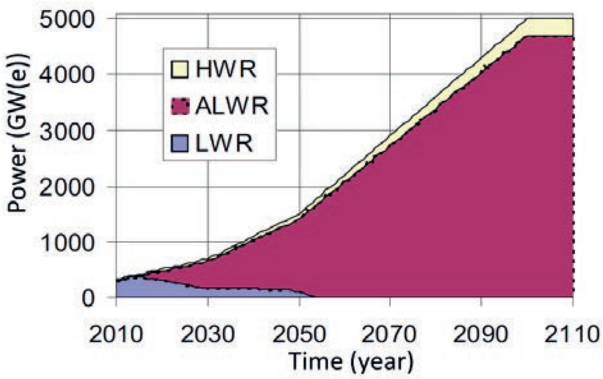
FIG. 3.250. Nuclear power structure, high demand, NG3 [3.12].

By 2100:

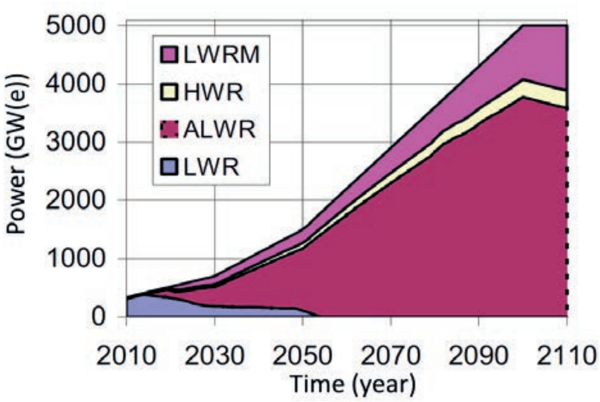
— Around 96% of electricity demand is generated by thorium based nuclear power plants.
— Annual plutonium discharges are decreased by a factor of around 1.9 for LWR0 introduction and by a factor of around 2.8 for LWR0 and HTR introduction, in comparison with the BAU scenario.
— Annual minor actinide discharges are decreased by a factor of around 1.9 for LWR0 introduction and by a factor of around 2.8 for LWR0 and HTR introduction, in comparison with the BAU scenario.
— Spent fuel accumulations are approximately 826 kt (BAU), 1142 kt (LWR0) and 357 kt (LWR0&HTR).
— Cumulative natural uranium consumption is increased approximately 40% for LWR0 introduction and for LWR0&HTR introduction, in comparison with the BAU scenario.
— Enrichment requirements are increased by a factor of around 1.9 for LWR0 introduction and by a factor of around 1.2 for LWR0 and HTR introduction, in comparison with the BAU scenario.
— Fuel fabrication requirements for thorium fuel cycle are around 76% of the total fuel fabrication requirements.
— Reprocessing requirements for thorium fuel cycle are around 100% of the total reprocessing requirements.

(b) Comparison of scenarios BAU, SLWRM and LWR12&HWR12

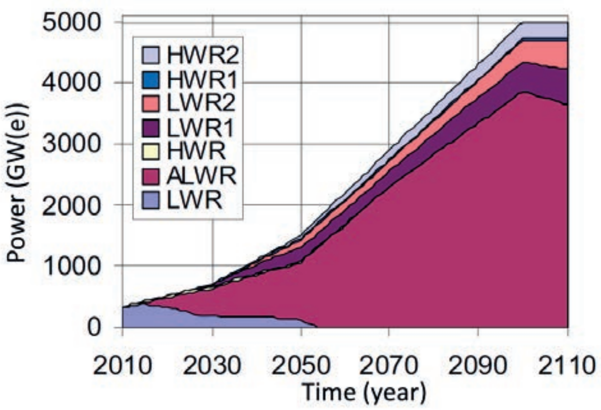
Figure 3.251 displays the results for thorium introduction in the BAU case (i.e. when only LWRs and HWRs are available). According to GAINS considerations, the BAU option serves as the reference fuel cycle. In addition to conventional LWRs and HWRs, the SLWRM option considers the use of MOX fuel consisting of depleted uranium and plutonium in ALWRs. The thorium option LWR12&HWR12 is based on LWR1 using Pu-Th fuel, LWR2 using Pu-U3-DU fuel, HWR1 using Pu-Th fuel and HWR2 using Pu-U3-Th fuel. In this case, the transition to thorium could be done through the incineration of civilian grade plutonium and achieving reduction of existing spent fuel stockpiles. Figure 3.251(a) shows the power demand trend of each reactor type for the BAU option. The ALWR



(a) BAU, global high case scenario



(b) SLWRM, global high case scenario



(c) LWR12&HWR12, global

FIG. 3.251. Nuclear power demand structure [3.12].

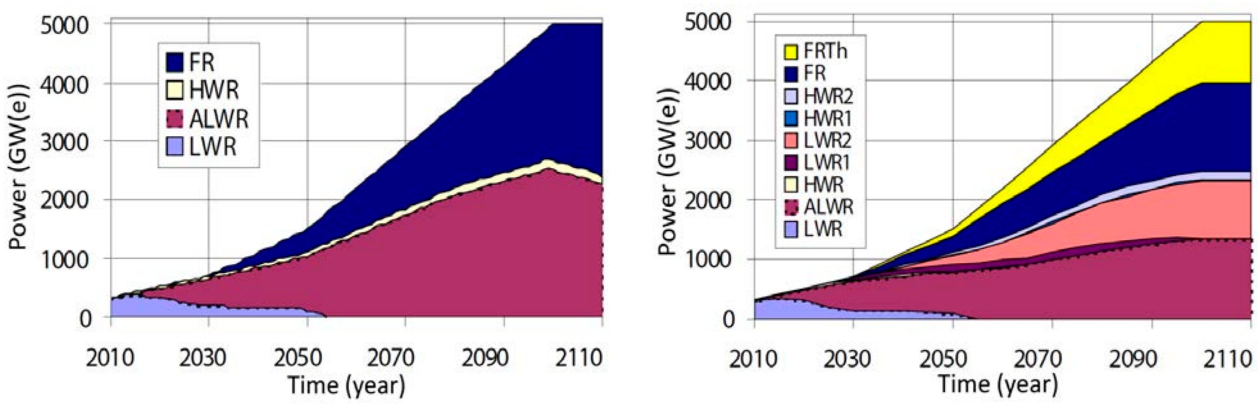
is introduced from 2015 and replaces the LWR. The HWR keeps its power share around 6% of the total nuclear power. By 2100, the share of thorium based nuclear power plants reaches only around 23% of the total nuclear generation. For comparison, the share of MOX based nuclear power plants is shown in Fig. 3.250(b) — about 18% of the total nuclear generation.

By 2100:

— Around 23% of electricity demand is generated by thorium based nuclear power plants.
— Cumulative natural uranium consumption is decreased by around 20% in comparison with the BAU scenario.
— Enrichment requirements decrease by around 24% in comparison with the BAU scenario.
— There is no accumulation of reprocessed plutonium; the annual plutonium discharge/consumption is around 1.5 kt/year.
— The annual rate of ^{233}U discharge/consumption is around 0.45 kt/year.
— Spent fuel accumulation decreases from around 5800 kt to 520 kt.
— Fuel fabrication requirements for thorium fuel cycle are around 36% of the total fuel fabrication requirements.
— Reprocessing requirements for thorium fuel cycle are around 34% of the total reprocessing requirements.
— Annual minor actinide discharge increases from around 0.12 kt/year to 0.15 kt/year.

(c) Comparison of scenarios BAU, SFR and FRTh&LWR12&HWR12

Figure 3.252 presents thorium introduction in the case of implementing fast reactors in the high demand scenario. Three options are compared: BAU, SFR and FRTh&LWR12&HWR12. The thorium option FRTh&LWR12&HWR12 is based on a fast reactor with a thorium blanket and thermal reactors LWR1, LWR2, HWR1 and HWR2. The transition to a closed fuel cycle involves incineration of civilian grade plutonium in fast and thermal thorium reactors. Figure 3.252(b) shows the power demand trend of each reactor type for the BAU option. According to the GAINS approach, HWRs keep around 6% share of the total nuclear power produced by thermal reactors. The share of thorium based nuclear power plants comes to about 27% of the total nuclear generation by 2100. In turn, this share is divided approximately fifty-fifty between fast and thermal reactors. Figure 3.252(a) shows the power demand structure for fast reactor options. The fast reactor share is around 47% by 2100. According to the GAINS reprocessing conditions, the HWR spent fuel is not reprocessed for the case involving fast reactors.



(a) SFR (b) FRTh&LWR12&HWR12

FIG. 3.252. Nuclear power demand structure [3.12].

By 2100:

— No accumulation of reprocessed plutonium; annual plutonium discharge/consumption decreases by a factor of around 1.5 for FR_Th, in comparison with fast reactor introduction.
— Annual ^{233}U discharge/consumption is around 0.4 kt/year.
— Spent fuel accumulation is less for FR_Th, in comparison with fast reactor introduction.
— Cumulative natural uranium consumption decreases from around 40 million t (BAU) to around 27 million t for fast reactor and FR_Th introduction, in comparison with the global BAU scenario.
— Enrichment requirements for fast reactor and FR_Th introduction decrease by a factor of around 2, in comparison with the BAU scenario.
— Annual minor actinide discharge is approximately identical for all scenarios.
— Fuel fabrication requirements for thorium fuel cycle are around 40% of the total fuel fabrication requirements.
— Reprocessing requirements for thorium fuel cycle are around 39% of the total reprocessing requirements.

(d) Comparison of natural uranium consumption in various options in the high case scenario in the NG1b group

Figure 3.253 presents cumulative natural uranium consumption for various reactor combinations in the group of countries NG1b (countries with fast reactors and closed fuel cycle with fast growth of nuclear in the 21st century). BAU and FR0 cases are added for comparison. The BAU option has the largest uranium consumption, followed by the options that involve reprocessing and then fast reactor options. In fast reactor variants the consumption of uranium depends mainly on the share of LWRs remaining in the scenario, with the share of LWRs a result of balances of plutonium and ^{233}U in NESs.

(e) Economic considerations of thorium utilization

The economic considerations of thorium utilization is analysed in Ref. [3.12]. LUEC was calculated on the basis of technical and economical inputs provided above. The real discount rate was assumed to be 0.04, which is a rather low value that increases the importance of fuel cost compared to capital cost and probably disguises some of the deficiencies of reactors with high capital costs but low fuel expenses, such as FBRs. The results of the calculations are represented in Fig. 3.254 for 11 reactors and several values of the cost of natural uranium.

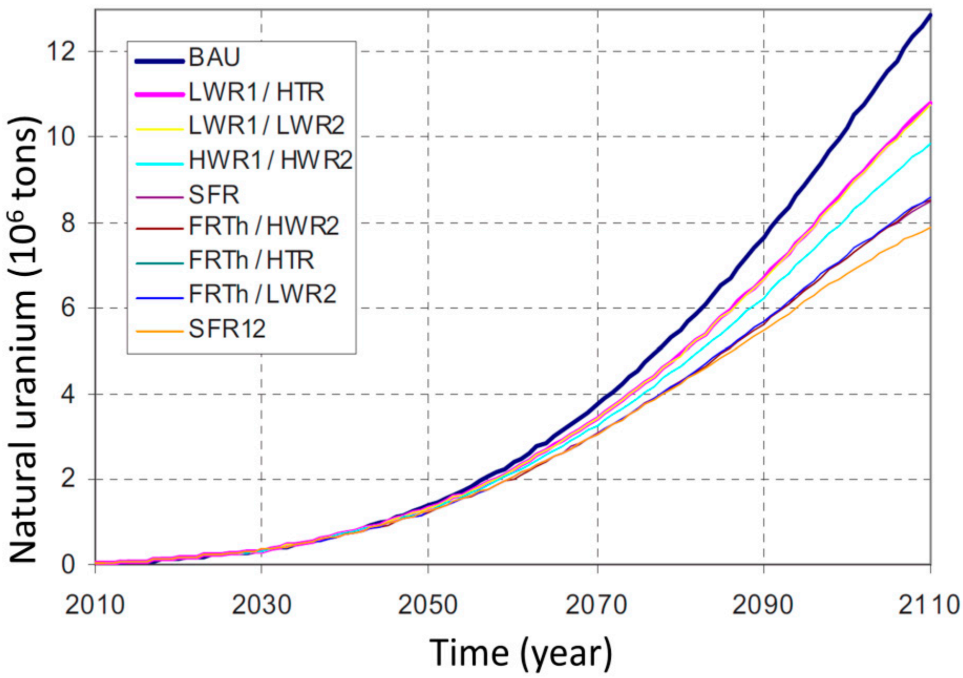


FIG. 3.253. Cumulative natural uranium requirements, NG1b [3.12].

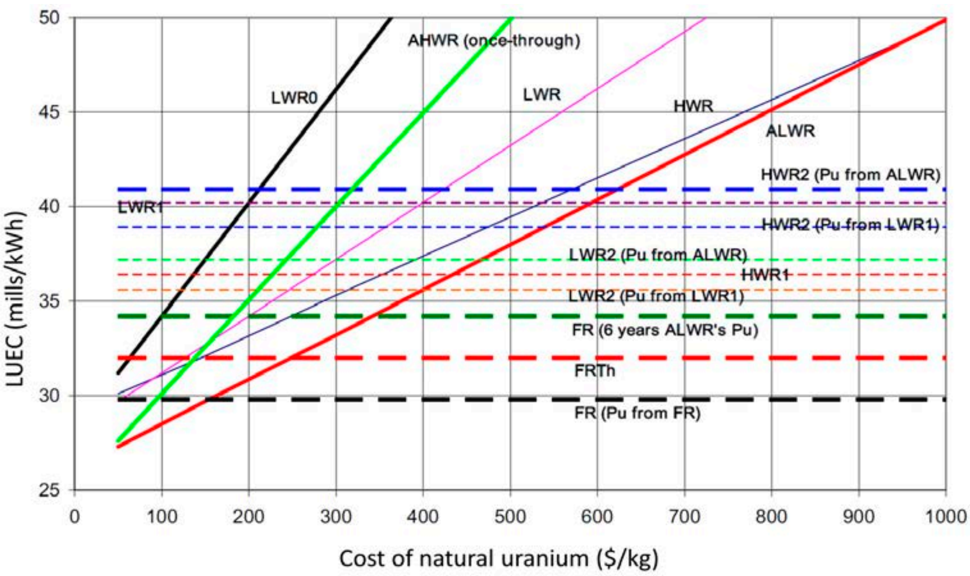


FIG. 3.254. Levelized unit energy cost depending on natural uranium cost [3.12].

The relatively low costs of the energy are a result of the moderate value of the real discount rate applied and the assumed input data, including optimistic assumptions on the trends of cost data. Unlike thermal reactors — where the source of fissile material does not significantly affect the levelized (i.e. constant for the full reactor lifecycle of 60 years) cost of electricity — costs for FBRs consuming plutonium from ALWR spent fuel during their first six years in operation are 15% higher than in the case of consuming its own plutonium. That means that all FBR programmes pass through a stage of very expensive fuel at their initial stage. Additional constraints, including availability of plutonium and its cost, should also be considered in the upcoming scenario studies. The same effect of higher plutonium and electricity costs occurs at the initial stage of industrial deployment of fast reactors with thorium blankets (FRTh).

AHWRs utilizing thorium in a once through mode produce some of the cheapest electricity when the cost of uranium is low, and may be competitive against conventional water cooled reactors up to the cost of US $150/kg of natural uranium. In a once through fuel cycle, AHWRs have one of the steepest growths of the energy cost from uranium cost because of the high enrichment of uranium fraction of fresh fuel and relatively high share of ^{235}U in its spent fuel. At a higher cost of uranium, an AHWR programme will be compelled to introduce reprocessing. A closed fuel cycle based on thorium reactors may become competitive against the traditional thermal reactors in a once through fuel cycle when the cost of natural uranium approaches US $400/kg. It should be noticed that the calculated levelized costs of electricity are only preliminary estimations and are subject to further considerations and future updates as new input data and advanced economic models are produced.

3.4.2.5. Conclusions

Many reactor types, including LWRs, HWRs, fast reactors, HTRs, molten salt breeder reactors, can use thorium or ^{233}U as a fuel, with variable efficiency. Twelve scenarios for thorium fuel cycle introduction were considered and compared to four scenarios of a ‘traditional’ uranium/plutonium fuel cycle. The findings do not claim to be complete or comprehensive, but they do demonstrate points of concern and should provide an incentive for further analysis and development.

The introduction of thorium fuel to once through fuel cycles involving modern LWRs may increase uranium consumption, the growth of necessary enrichment and fuel manufacturing costs, and the amount of the spent fuel to be unloaded. The benefits of this scenario would be limited to the decrease of plutonium and minor actinide content in the spent fuel. Nevertheless, optimization of the thorium/uranium ratio in a LWR core may lead to the improvement of the once through scenario result, and this issue may be worthy of further consideration.

The introduction of thorium in a once through fuel cycle based on AHWRs may provide more advantages, even comparing to designs for ALWRs. HWRs can efficiently exploit thorium based fuel for breeding of ^{233}U, burning and for applications without recycling. For the once through fuel cycle cases, the higher burnup scenarios lead to a higher percentage of energy from thorium. The percentage of energy from thorium is higher for the low burnup recycle case than the high burnup recycle case.

Thermal thorium reactors in a closed nuclear fuel cycle can provide approximately the same enhancements to uranium economy, enrichment, and fuel manufacturing efforts as the use of uranium/plutonium–MOX fuel. The decrease of minor actinide production via thorium utilization only takes place when the designer succeeds in avoiding plutonium utilization in the thorium based fuel, otherwise minor actinide production increases. The options that feature FBRs along with thermal reactors demonstrate similar rates of consumption of uranium, enrichment, fuel manufacturing and minor actinide accumulation, regardless of thorium utilization. Traditionally, thorium allows the amount of plutonium handled in the system to be minimized, but it leads to significant needs for reprocessing.

Consideration of economics shows that thorium reactors operating in a once through fuel cycle may be competitive with conventional uranium/plutonium reactors when the costs of natural uranium approaches around US $150/kg. A thorium fuel cycle with reprocessing may become competitive against a uranium/plutonium once through fuel cycle when the cost of natural uranium is higher than around US $400/kg. Taking into account some geographical and infrastructural conditions, the application of thorium may be considered as a complementary option for an NES with fast reactors, but it hardly can be competitive against a successfully deployed fast reactor programme.

3.5. SUMMARY OF FINDINGS

Case studies performed within the SYNERGIES project show the growing interest of Member States in long term analysis of nuclear energy evolution scenarios taking into account synergies among the various technologies and options for cooperation with other countries in fuel cycle back end that may help to ensure enhancing nuclear energy sustainability on national, regional and global levels. Of the 27 case studies summarized in Table 3.1, 21 explicitly addressed synergies in technology, 20 synergistic collaboration in fuel cycle back end with a link to synergies in technology. Six studies touched upon possible cooperative solutions on a regional level, another six upon possible regional and global solutions, and yet another study upon possible global solutions. Even if synergies offered by technology and cooperation are not addressed explicitly, the scope and results of the studies often suggest that options for cooperation might exist and could, therefore, be addressed in further studies.

The economics — first of all the LUEC — is in most cases the primary criterion to select among various fuel cycle back end cooperative solutions; however, several studies indicate, while some state it explicitly, that the discount rate used in LUEC makes it alone insufficient to address longer term sustainability solutions. Cash flow analysis is then needed to amend LUEC to arrive at a real scale of problems that future generations may face owing to the decisions made today.

With LUEC the first choice criterion, it goes by default that Member States planning to develop and deploy, or are already actually deploying, innovative nuclear technologies de facto are spending and will spend billions of US dollars for research, development and demonstration (RD&D) to bring new technologies up to the NOAK unit [3.52], only for which they are targeting competitive LUEC. This being observed, the least cost energy model appears to be only conditionally applicable to technology holder countries who apparently have other motivations for longer term investments in RD&D, such as an intention to cater sustainably to the needs of sometimes huge domestic markets, as well as an intention to become world or regional leaders in future export supplies of technologies for nuclear power.

Most of the case studies performed have not addressed legal or institutional impediments for cooperation among countries in fuel cycle back end, with the study in Section 3.3.10 (Modelling of regional collaborative deployment scenarios aimed at solving the problem of accumulation spent nuclear fuel inventory) being a notable exception. However, technical impediments to realize particular scenarios targeted at the minimization of HLW through spent fuel recycling and actinide transmutation are addressed explicitly in a number of case studies. Those are related to maintaining the required plutonium balance which is affected by demand, production and spent fuel cooling time, transmutability of particular radiotoxic minor actinides in different reactor configurations, as well as sharply uneven demand in reprocessing capacities or practically too high deployment rates for nuclear power plants.

3.5.1. Scenario family A

Proven options for synergistic collaboration exist, for example, such as the EU limited LWR spent fuel reprocessing[17] and MOX fuel supply for a single recycle in LWRs, as shown in Section 3.1.5 ('EU27 scenario' with the extended use of regional fuel cycle centre composed of the La Hague and MELOX facilities). Such services provide for a variety of offers, wherein the supplied MOX fuel is not necessarily produced from the LWR spent fuel imported from a recipient country, and could be expanded towards increasing demand within the present century. Owing to the commercial nature of the services which involve nine EU Member States, no economic data are provided. However, Ref. [3.104] suggests important non-economic considerations that are main drivers for such services. They are related to risk reduction with respect to:

— Non-proliferation and security;
— Environmental impact and footprint;
— Public acceptance.

They also help to improve nuclear system performance, specifically with regard to [3.104]:

— Increased energy independence.
— Optimized cost of nuclear electricity.
— Preservation of natural resources (for scenarios of the A family, the maximum achievable effect is, however, limited by a 10% reduction in natural uranium consumption).
— Minimization of generated waste and deep geological disposal requirements.

Altogether, these factors may outweigh the associated slight increase of fuel costs. The increase of the natural uranium price will naturally make this option more economically attractive. Section 3.1.5 also points to some impediments that could be observed on the way of MOX fuel single recycling in LWRs in higher growth rate scenarios with broader reprocessing of LWR spent fuel, as related to long cooling time of spent fuel.

The two case studies coming from Canada, provided in Section 3.1.3 (Economic value of uranium recovered from LWR spent fuel as fuel for HWRs) and Section 3.1.4 (A reactor synergy: using HWRs to transmute Am from LWR spent fuel), suggest yet another possible synergy in technologies and in cooperation among countries related to the use of reprocessed uranium from LWR spent fuel in HWRs with an option to add an element containing americium from LWR spent fuel. It is noted that, if realized, such an option could also boost plutonium recycling in MOX fuel, as plutonium is actually a by-product of uranium reprocessing.

The study on reprocessed uranium recycling in HWRs provides an estimate of the economic savings for HWR utility coming from reprocessed uranium use as compared to natural uranium use under certain assumptions regarding natural uranium and reprocessing costs.

The scenario analysis of reburning LWR americium in HWRs shows the associated reduction of requirements to HLW disposal and provides an estimate of possible economic benefits to HWR utility depending on disposal costs, partitioning costs and natural uranium price. It should be noted that a practical realization of a scenario with reburning LWR americium in HWRs will require development of new safeguards arrangements, as separated americium is rated as direct use material.

The case studies from Armenia, in Section 3.1.2 (Assessment of impact of fuel cycle back end options on levelized unit electricity cost of produced electricity based on nuclear fuel cycle in Armenia), and Indonesia, in Section 3.1.6 (Comparative assessment of collaborative fuel cycle options for Indonesia) represent the current standpoints of a country with a small electricity grid and a newcomer country, respectively. They both conclude a once through fuel cycle may be the best option for the period until the middle of the century.

Armenia is looking to export its spent nuclear fuel to the vendor or a fuel cycle back end service provider, but concludes, through economic analysis, that such export would be preferable after the expiration of the project period

[17] A government driven endeavour on a national level in just two countries.

of the spent fuel dry storage facility. The Indonesian study examines a number of fuel cycle options, including a closed fuel cycle with fast reactors, MOX recycle in LWRs and ^{233}U–thorium fuel cycle. It concludes that, if natural uranium prices go up, single recycle of MOX fuel could be introduced. It also mentions that the coupling of MOX recycle with fast reactor recycle might become an attractive option in a more distant future. Cooperation with technology holder countries is mentioned with respect to these fuel cycle options.

Case studies from Romania, in Section 3.1.8 (National Romanian scenarios with reliance on domestic and imported U/fuel supply, by considering regional collaboration in nuclear fuel cycle and including economic analysis), and Ukraine, in Section 3.1.9 (Scenarios with replacement heat generation), both consider regional solutions for spent fuel repository. It should be mentioned that Ukraine has also considered options of fuel return to the vendor but found them currently non-competitive to long term storage. Regional solutions, if they become available, are in both cases considered in view of possible reductions in costs.

A case study from Argentina, in Section 3.1.1 (National Argentine scenario with cooperation options), highlights technology potential and deployment status of nuclear energy in Argentina and suggests in the future Argentina might become a regional/global supplier of nuclear technology and services.

A case study from Japan, in Section 3.1.7 (Analysis of ALWR based scenario), takes a global approach to examine differences between homogeneous and heterogeneous world models in a scenario with the introduction of ALWR with spent nuclear fuel reprocessing and single recycle as MOX fuel. Substantial differences between the two models with respect to ALWR MOX share, reprocessing capacity and HLW volume reduction are revealed and quantified.

3.5.2. Scenario family B

Case studies on scenarios with the introduction of a number of fast reactors to support multi-recycling of plutonium in LWRs and fast reactors (Scenario family B) address the situations when fast reactor deployment is delayed or progressing quite slowly, which is the actual case observed around the world today. These studies aim to show what can be achieved already in near and medium terms with an initially small number of fast reactors in terms of LWR spent fuel management and fissile resource savings. The scenarios in family B can improve natural resource utilization by a factor exceeding ten. The conclusions of these studies are as follows.

The Russian–French study, in Section 3.2.1 (Evaluation of national NESs based on Pu cycle with the introduction of a number of fast reactors), examined some model national scenarios with near term options to start minimizing HLW from spent nuclear fuel of LWRs through the introduction of a limited number of fast reactors.

The French part of this study shows that plutonium multi-recycling in both thermal and fast reactors is possible with a symbiotic fleet composed of LWR UOX, LWR MOX and SFRs optimized to reach equilibrium between plutonium consumption and production. The plutonium produced in UOX LWRs is used to feed LWR MOX as in France, and SFRs are used to recycle plutonium from spent LWR MOX fuel to improve its quality so it can finally be used together with spent UOX fuel to produce fresh LWR MOX fuel. It is shown that with only one quarter of SFRs in the fleet progressive accumulation of plutonium could be reversed and natural uranium requirements could be halved.

In the Russian part of the study, an option for resolving the problem of spent nuclear fuel based on the use of technologies that rely on the near term BN type SFR reactors and MOX fuel was explored. To a certain extent, the proposed approach is similar to that considered in the French part of the study. It differs however, in that the Russian part of the study focuses on solving of the problem of WWER spent nuclear fuel in the medium term by reprocessing it and using the recovered plutonium and uranium for startup loads of a small number (10% of the overall capacity) of BN-1200 type SFR reactors, with no immediate MOX fuel use in WWER type LWRs. This option would allow to create preconditions for further multiple recycling of MOX fuel for complete and efficient resolution of the problem of WWER spent fuel, which would allow to decrease storage capacity and minimize the accumulation of radiotoxic ^{241}Am during spent fuel storage. In contrast with other options, such as direct disposal of spent fuel or MOX recycling in LWR, the proposed scenario would preserve all plutonium accumulated in WWERs in a consolidated form as a startup resource for potential future large scale deployment of advanced or innovative fast reactors and closed nuclear fuel cycles.

The study in Section 3.2.2 (Global scenarios with the introduction of a number of fast reactors under uncertainties in the scale of nuclear energy demand and in the nuclear power structure) was conducted jointly by the IAEA and Russian participants of the project. This study, building upon the GAINS analytical framework [3.52], explored the scenarios of transition to a global sustainable NES under uncertainties in the scale of nuclear energy demand and in the nuclear power structure. The low GAINS scenario (with practically no increase in nuclear capacity against the present) was considered, and the prime objective was to address the problem of spent nuclear fuel starting from the near term by using the existing reactor technologies (LWRs) and SFRs with MOX fuel. For the scenario considered it was assumed that plutonium from the spent nuclear fuel of MOX fuelled fast reactors could be recycled as MOX fuel in the current advanced LWRs (1/3 core), followed by multi-recycling in the upcoming fast reactors.

Heterogeneous world model developed in the GAINS project [3.52] was used. It was assumed that spent nuclear fuel from LWRs of the newcomer countries will be sent to technology holder countries for reprocessing and fabrication of the MOX fuel to be used in fast reactors in the technology holder countries. In this, technology holder countries additionally supply MOX fuel for use in LWRs of newcomer countries. It was shown that, if nuclear energy demand increases in the medium and long term, fast reactors with the breeding ratio of 1.16 loaded by MOX fuel could help to meet the energy demand. All scenario analyses performed in this study employed the nearer term fast reactor technologies, including SFRs with breeding ratios of 1.0 (break-even) and 1.16. Nuclear power plants based on such technologies are either in a construction phase or at an advanced project development phase in several countries.

3.5.3. Scenario family C

Case studies on fast reactor centred scenarios consisting of scenarios with reprocessing of thermal reactor fuel to enable noticeable growth rate of fast reactor capacity (Scenario family C) represent the majority of all case studies performed and bring out many important findings. They address different strategies of fast reactor deployment and use to solve the problems of HLW progressive accumulation, fissile resource depletion and minor actinide transmutation. In the majority of cases, they address synergistic cooperation among countries (see Table 3.1). The scenarios in this family can help to improve resource utilization by a factor of 10–100. The major conclusions of these studies are as follows.

The case study in Section 3.3.10 (Modelling of regional collaborative deployment scenarios aimed at solving the problem of accumulating spent nuclear fuel inventory) was conducted cooperatively by experts from Armenia, Belarus, the Russian Federation and Ukraine and was based on heterogeneous world model approach of the GAINS analytical framework [3.52] 'downscaled' to a regional revel. Within such a heterogeneous model, Armenia, Belarus, the Russian Federation and Ukraine belong to different strategy groups. The Russian Federation belongs to the nuclear energy group which pursues a general strategy to recycle spent nuclear fuel. This group plans to build, operate and manage used fuel by recycling facilities and permanent geological disposal facilities for highly radioactive waste. Ukraine can be placed into another nuclear energy group, which follows a strategy either to directly dispose spent fuel, or to reprocess it abroad. Armenia and Belarus have a general strategy to use fresh fuel supplied from abroad and to send used fuel abroad for either recycle or disposal, or the back end strategy is undecided, and are thus part of yet another energy group, in terms of the GAINS framework.

The objective of this study was to explore the scale of possible regional activities between different country groups in the short term, and to analyse scenarios for the potential initial phase of regional cooperation on the back end of nuclear fuel cycle. Although the participants have used some national projections for nuclear power evolution, nothing is based on actually approved national decisions or plans and, therefore, the study is of a model nature, with its conclusions potentially valid for many other situations that might be observed worldwide.

The study concluded that international (regional) collaboration in fuel cycle back end is likely an inevitable solution on the path towards regionally/globally sustainable nuclear power. The following drivers supporting a potentially 'win-win' strategy for cooperation were found:

— Substantial savings of natural uranium for collaborating partners due to substitution of ^{235}U in UOX nuclear fuel of WWER type reactors[18] by the plutonium separated from UOX spent nuclear fuel of WWER and used in MOX fuel of fast reactors;
— A potential to collaboratively manage spent nuclear fuel and plutonium to avoid their excessive accumulation;

[18] It will also be true for other types of LWR.

— Savings of financial and manpower resources for users to develop expensive national closed fuel cycle infrastructure while retaining all of the benefits of the closed nuclear fuel cycle;
— Expansion of nuclear energy business for the technology holders and associated reductions in the cost of fuel cycle back end services for users;
— A possibility to utilize cheaper categories of uranium for both users and technology holders.

Along with the drivers, some impediments for the regional collaboration were identified:

— Technical and institutional procedures are not developed to the necessary level of detail; the price formation in this area is not transparent and does not stimulate implementation of reprocessing abroad.
— Political and economic instability may hamper multilateral collaboration.
— Concerns over security of supply.

The study also identified some issues requiring further research, including:

— Reduction of the uncertainty of initial data on the cost of the fuel cycle stages, including transport;
— Development of a methodology to estimate the value of spent fuel reprocessing products (e.g. regenerated uranium and plutonium);
— Clarification of the timing of spent fuel deliveries, storage periods and conditions of reprocessing, of the inventory of returned materials, of the uncertainty of economic data, among other things.

The case study in Section 3.3.8 (Sustainable regional scenario with ‘adiabatic’ lead fast reactors in selected countries), conducted by participants from Italy, compared multinational and national approaches to nuclear fuel cycle for a scenario with the deployment of a fleet of PWRs and subsequently, at a certain time, the one of LFRs in several European regions with high projected demand for CO_2 free baseload electricity and no negative public stance regarding nuclear energy. The performed model study is interesting in that it explores the cooperation potential among Italy, a country which, on the one hand, has a moratorium on nuclear energy, and on the other, maintains nuclear education, R&D and industrial capacity, has a utility that operates some nuclear power plants abroad and takes a lead in the development of a liquid lead cooled nuclear fast reactor within a Generation IV International Forum programme and the countries from South-East and Central East Europe potentially looking for introduction or expansion of their nuclear power programmes and some countries from South-East and Central East Europe that are assumed to continue looking from embarking upon a nuclear energy option or extending their ongoing nuclear energy programmes.

The study, some intermediate results of which were presented in Ref. [3.85], assumed:

> “new possibilities are emerging [across Europe] to render competitive electricity from Nuclear Power Plants (NPPs) owing to two factors: the first one, which is the fast growth of High Voltage lines interconnecting the European countries’ national electrical grids, this process being triggered by [a] huge increase of the installed intermittent renewable electricity sources (Wind and PV [photovoltaic]); and the second one, determined by the carbon-free constraints imposed on the base load electricity generation. The countries that due to public opinion pressure can’t build new NPPs on their territory may find it profitable to produce base load nuclear electricity abroad, even at long distances, in order to comply with the European dispositions on the limitation of the CO_2 emissions.”

Evaluated were material balances for the front and back end of the nuclear fuel cycle as corresponding to the installed nuclear capacity. Specifically, the expenditures associated with the enrichment and separation flows were comparatively assessed taking into account the economy of scale factors for two different scenarios. In the first one, a coordinated management of the nuclear fuel cycle (i.e. the synergic case) among all of the countries is established; in the second scenario, there is no such synergy. The scenario analysis is performed from 2020 until 2120.

The analysis performed in this study indicates the economies of scale in fuel enrichment and used fuel reprocessing services have a potential to cut down fuel costs by 34–49%. Besides the economic benefits, environmental benefits are determined with a cut in the natural uranium consumption of the 3% thanks to the use of an unutilized fuel resource, as is the depleted uranium, for feeding the fissile self-sufficient lead cooled reactors. If some plutonium could be acquired outside the regions considered (establishing synergies with them or generated with appropriated breeder reactors), different shares of PWRs and LFRs in different regions could be considered for a synergistic case.

The case study in Section 3.3.2. (Preliminary analysis of the nuclear energy development scenarios based on U–Pu multi-recycling in China) aimed at examining the potential of indigenously developed SFRs to meet high national nuclear energy demand targets in short and medium terms. Considered is a demanding scenario with national nuclear capacity reaching 400 GW(e) by 2030. To meet this capacity, the operating and newly deployed PWRs are amended by fast reactors with MOX or metallic fuel. It is shown that meeting the challenging 2030 target requires conducting RD&D on, and implementing, the metal fuelled SFRs with breeding ratios of above 1.4 and advanced reprocessing technologies. The Chinese study does not address cooperation with other countries in fuel cycle back end, such as offering back end fuel cycle services to technology user and newcomer countries, presumably, because of a huge national demand in nuclear energy, the meeting of which is an ultimate priority in the short and medium term.

The case study in Section 3.3.13 (Scenario with the WWER–fast reactor collaborative deployment) was conducted by participants from Ukraine and developed a pathway for Ukraine to decrease spent nuclear fuel accumulation through implementation of fast reactors. Considered in this study were medium and long term scenarios with Generation III+ and IV reactors, spent nuclear fuel reprocessing, international centres for long term spent fuel storage and/or disposal, but also HWRs operated on reprocessed uranium from LWR spent fuel. The closed nuclear fuel cycle based on fast reactors in Ukraine was found to be economically unattractive, due to:

— Availability of large uranium reserves;
— High cost of fast reactor construction;
— High cost of spent nuclear fuel reprocessing;
— High cost of fresh and MOX fuel fabrication for fast reactors.

The winning medium term scenario appeared to be the one based on HWRs fed with regenerated uranium — for which additional investigations could be performed.

With regard to longer term limitations on spent fuel accumulated (conditioned by storage capacities), it would require spent fuel reprocessing and commissioning of fast reactors and LWRs with MOX fuel to start from 2045. Closing the nuclear fuel cycle with a fast reactor programme would significantly decrease the amount of spent fuel accumulation. The study provided electricity cost estimates for the scenarios with fast reactor deployment, but pointed to a high uncertainty of these evaluations due to the unknown cost of fast reactors. It also suggested the most sustainable approach would involve developing international cooperation in fuel cycle back end, specifically for the reprocessing of spent nuclear fuel from LWRs and fabrication of MOX and reprocessed uranium fuel.

The case study in Section 3.3.9 (Long term scenario study for nuclear fuel cycle in Japan) investigated the possible role of fast reactors and a closed nuclear fuel cycle in three national scenarios representing a reduction of the role of nuclear energy in national energy mix, as a follow-up to energy policy change following the accident at the Fukushima Daiichi nuclear power plant, in 2011. The scenarios included keeping the nuclear capacity constant at different levels, as well as gradually bringing it down to zero after 2030, again from different levels. The fuel cycle options considered:

— Deployment of fast reactors to replace LWR after 2050, with full reprocessing;
— Partial reprocessing limited to Rokkasho plant capacity;
— Direct disposal of all spent nuclear fuel.

The indicators considered in this study were nuclear capacity, natural uranium demand, plutonium stockpile and inventory, spent fuel stockpile, and radioactive waste generation and disposal. The study concluded that the full reprocessing strategy has a potential to reduce natural uranium demand, spent fuel stockpile, radioactive waste and plutonium inventory compared to direct disposal strategy and the partial reprocessing (see Annex XI on the CD-ROM accompanying this publication) in all considered scenarios of nuclear capacity evolution. The reduction effect is especially significant for the cases of capacity decrease after 2030. The study is a good illustration of a positive role the fast reactors and closed nuclear fuel cycles could play in the nuclear phase out and no growth scenarios. Their capacity being in place, they could also provide back end services to other countries, such as for example, MOX fuel supply for use in LWRs.

The case study in Section 3.3.5 (Comparative economic analysis of selected synergistic and non-synergistic GAINS scenarios) examines the magnitude of possible effects in investment cost reduction by to centralization of fuel cycle back end facilities, owing to the economy of scale effects. The database of economic characteristics of nuclear fuel cycles and nuclear reactors, given in Appendix II, was used for this purpose. The study builds upon the GAINS synergistic and non-synergistic heterogeneous world models, and also provides for interpretation of its results at regional levels.

An important insight produced by the study is that, with a discount factor being used, LUEC alone is not an adequate indicator for comparative analysis of longer term sustainability options — the burdens to future generations which might be high on the absolute cost scale tend to be flattened or nullified by LUEC if the consideration period is remote. LUEC analysis then needs to be amended by cash flow analysis, and this analysis shows that:

— For the synergistic case, the decrease of fuel cycle investments for the synergistic case may reach 14% in the short term, 52% in the medium term and 62% in the longer term, compared to a non-synergistic case.
— Total investments during entire modelling period (2015–2100) would then be 46% less for the synergistic case.

Taking into account that a closed nuclear fuel cycle infrastructure development, as the study points out, typically costs a few tens of billions of US dollars, the above mentioned savings are likely to make sense.

The case study in Section 3.3.6 (Sensitivity analysis of the shares of NG1/NG2/NG3 country groups in GAINS scenarios) is a follow-up on the heterogeneous synergistic world model developed in the GAINS project [3.52]. The goal of this sensitivity study was to determine the impact of changes in the shares of non-personified groups of countries with different policies regarding fuel cycle back end (NG1, NG2 and NG3) on key indicators of the GAINS analytical framework [3.52]. In this framework, NG1 represents technology holder countries going for closed fuel cycle and fast reactor programmes, NG2 represents technology holders running thermal reactors in a once through cycle with spent fuel being directly disposed or sent to NG1 for reprocessing and reuse in NG1 fast reactor programme, NG3 represents newcomers who intend to operate thermal reactors and cooperate with NG1 and NG2 in nuclear fuel cycle front end and back end. For the GAINS studies [3.52], the NG1:NG2:NG3 ratio was fixed at 40:40:20. The change in NG1:NG2 proportion takes into account a possible transition from one group to another. NG3 share variation considers possible market share of NG3.

In particular, this study noted significant effects in saving natural uranium resources and reducing spent nuclear fuel amount are for options with a higher share of NG1, a low share of NG2 and for the high nuclear energy growth scenario. With a higher NG3 share (more than 40% in the considered case), stresses begin to appear in NG1. The spent nuclear fuel sent by NG3 to NG1 cannot be fully reprocessed even with the sufficient reprocessing capacity, because the fast reactor deployment rate is limited by the overall nuclear energy demand growth rate specified for NG1. Nevertheless, in this case the synergistic approach results in a significant reduction of the requirements for long term storage of spent nuclear fuel.

For NG1 with high nuclear energy demand growth and sufficient reprocessing capacities, all spent nuclear fuel from NG2 and NG3 available for reprocessing was shown to be fully ‘consumed’ by 2070. This highlights that only a synergistic global NES with the appropriate structure is capable of providing a global reduction of spent nuclear fuel accumulation. In the case of high NG3 share all spent sent to NG1 group cannot be fully reprocessed due to the limited overall demand growth rate and consequently the limited fast reactor deployment rate in NG1. However, even for this case the requirements for long term storage of spent nuclear fuel could be significantly reduced for synergistic approach. For high nuclear energy demand growth and sufficient reprocessing capacities in NG1 all spent nuclear fuel sent to NG1 could be reprocessed by 2070. This highlights the ability of a synergistic global NES with the appropriate structure to solve an issue of global spent nuclear fuel accumulation [3.81].

The study in Section 3.3.7 (Alternative deployment strategy of fast reactor startup on enriched U fuel) was conducted by experts from the Russian Federation with the support from the IAEA. It took a global approach to compare different strategies of fast reactor startup: from uranium–plutonium loads obtained from the reprocessing of LWR spent fuel versus from enriched uranium load, with subsequent recycling of fast reactor fuel in both cases. The study used the GAINS analytical framework scenarios and, within the fast reactor domain and partly LWR domain of these scenarios, considered SFRs started from MOX obtained through reprocessing of LWR spent fuel and heavy liquid metal cooled reactors started from enriched uranium fuel.

Heavy liquid metal cooled fast reactors started from enriched uranium load are being considered to replace completely the LWR fleet. At a breeding ratio slightly above 1.0, they are capable of fissile self-sufficiency, with their refuelling in the equilibrium state being essentially removal of fission products and addition of the depleted uranium. Notwithstanding the higher uranium enrichment (still below 20%), they are thus capable of natural uranium savings against LWRs which operate in a once through cycle and have conversion rates at the 0.55 level. At the same time, fast reactors with enriched uranium startup load are not deemed to deal with the spent fuel already accumulated through LWR previous operation, as well as that produced by LWRs that will still be in operation.

The objective of the study was to compare the impact of each of the alternative strategies and mixed deployment variants on the GAINS key indicators and infrastructure requirements on a global scale. The major conclusions are as follows:

— In the short and medium terms, introduction of the enriched uranium startup load makes it possible to realize a high scenario fast reactor deployment programme under LWR reprocessing capacity limitations. The fleet of fast reactors in the case of 100% fraction of the uranium load fast reactors could be increased by a factor 1.5 compared to the case when all fast reactors start with MOX fuel obtained from reprocessed LWR fuel.
— By 2100, all options with fast reactors (MOX, uranium and mixed deployment) offer comparable natural uranium savings in comparison with the business as usual case with thermal reactors in a once through fuel cycle.
— Use of enriched uranium for the first core load of a fast reactor requires more enrichment capacity.
— Options of fast reactor introduction with a uranium loaded fast reactor share of up to 50%, the rest being MOX loaded fast reactors, show positive effects on spent nuclear fuel accumulation — it drops down to a zero level in 2065, 2080 and 2090 for the uranium loaded fast reactor shares of 0%, 25% and 50%, respectively. Similar results are observed for the inventories of plutonium and minor actinides in long term storage facilities of LWR spent fuel.

Summing up the results of this study, mixed deployment of fast reactors started from the enriched uranium and MOX loads may be a reasonable strategy to implement a high capacity growth fast reactor deployment programme.

The case study in Section 3.3.11 (Homogeneous and heterogeneous world model scenarios with WWER-Ss, SMRs and HTRs, including non-electrical applications) was conducted by Russian participants of the SYNERGIES project to understand the potential of a supercritical LWR with a high conversion ratio (WWER-S) to address sustainability challenges to nuclear energy for both, once through fuel cycle and closed nuclear fuel cycle in a system which also includes fast reactors with a break-even breeding ratio (~1). Another objective was to examine how HTRs and SMRs (allowing for non-electrical applications) would affect material balances in an NES.

The studies performed show that WWER-Ss with a conversion ratio of about 0.8 coupled with the break-even fast reactors could meet the demands of a nuclear energy evolution scenario with 5000 GW(e) reached by 2100 in terms of natural uranium resources and HLW. For high global growth rates of nuclear energy, fast reactors with higher breeding ratios would be needed.

With regard to HTRs and SMRs, their inclusion in the system in reasonable numbers was shown not to downgrade significantly spent nuclear fuel reduction and fissile resource availability. Collaboration among countries with different policy regarding fuel cycle back end was proven important to ensure global sustainability of nuclear energy. In this, it was found that reasonable variations of the shares of different groups of countries [3.52] do not affect significantly the analysed key indicators.

Section 3.3.4 (A French study on radioactive waste transmutation options) is a summary of the study carried out by the CEA in collaboration with EDF, AREVA and ANDRA under a 2006 French law on waste management. The objective of the study was to obtain an assessment of industrial perspectives on partitioning and transmutation of long lived elements. The research was based on the analysis of technical and economic scenarios taking into account the possibilities of optimization between long lived HLW transmutation processes, their interim storage and their disposal in a geological repository. With SFR deployment considered in France for 2040, the study investigated:

— Plutonium recycling in SFRs (minor actinides are sent to waste);
— Plutonium recycling and minor actinides (or americium alone) transmutation in SFRs and in homogeneous mode (minor actinides are mixed with reactor fuel);

— Plutonium recycling and minor actinides (or americium alone) transmutation in SFR and in heterogeneous mode (putting minor actinides in radial blankets on a depleted UO_2 matrix);
— Plutonium recycling in SFRs and minor actinide transmutation in ADSs.

The major findings are the following:

— The transmutation of minor actinides significantly reduces their inventory in the geological repository; however, the immediate consequence of the reduction of the minor actinide content in the waste is an increase of the minor actinide inventory in the cycle (reactors and plants).
— Only the transmutation of all minor actinides, through multi-recycling operations in SFRs or ADSs, enables stabilization of their inventory over time.
— The transmutation of americium and minor actinides would result in a reduction by a factor up to 7.3 (americium) to 9.8 (minor actinides) of the footprint of the HLW disposal zone after an interim storage period of 120 years, a total reduction by a factor of 3 of the repository footprint taking into account ILW and LLW and common infrastructures. It is noted that transmutation of americium alone accounts for around 75% of the total possible effect of HLW disposal zone footprint reduction.
— In transmutation options higher contents of minor actinides at the fuel manufacturing and processing steps will require significant design modifications for dealing with obvious thermal and radiation protection problems. The complexity of the operations carried out during the operating phase (loading/unloading, interim waste storage, and transport) will also be increased.
— Scenarios involving the transmutation of all minor actinides are extremely impeded by the presence of curium and the implementation constraints often exceed that of the scenarios, in which only americium is transmuted, by one order of magnitude.
— The transmutation of curium raises design constraint issues for all facilities, whereas its impact on the reduction of HLW zones is low compared to the impact of americium transmutation.
— The economic studies conducted show that the cost increase related to the transmutation process could vary between 5–9% in SFRs and 26% in the case of ADSs.

In addition to this, the French study produced insights regarding a minimum risk stepwise strategy of transmutation implementation in SFRs.

The case study in Section 3.3.12 (Analysis of advanced European scenarios including transmutation and economical estimates) was conducted by Spanish participants of the SYNERGIES project and analysed in terms of available resources and economic implications the impact of the implementation of the four selected reference scenarios on a European nuclear fleet under the assumption of constant nuclear electricity demand. The reference scenarios were the following:

— A once through fuel cycle reference scenario with LWRs gradually replaced by an advanced LWR (in the study referred to as LWR GEN-III);
— A scenario where LWRs are replaced by LWR GEN-III after 2021 and by SFRs after 2040;
— A scenario similar to the previous one, by where 56% of the SFRs are loaded with transuranic based fuel;
— A scenario which assumes that minor actinide transmutation is performed exclusively with ADS units, while SFRs are dedicated to plutonium burning and breeding.

The indicators assessed included:

— Natural uranium and plutonium needs;
— Number of fast reactor units and ADS facilities to achieve an equilibrium content of minor actinides in the fleet;
— Minor actinide evolution for transmutation scenarios;
— LCOE for each scenario and by reactor type;
— Impact in the LCOE of main components.

The European electricity demand was assumed constant over the whole period of consideration from 2010 to 2210. The analysis performed has shown the feasibility of all considered scenarios in terms of fissile and fertile inventories (natural and depleted uranium, plutonium and minor actinides). Without a transmutation strategy for minor actinides, fast reactors reduce significantly the amount of plutonium in the final repository (to 1% of the total). The minor actinide incineration could be achieved both, with a strategy including SFRs for both electricity generation and minor actinide transmutation, and also in a strategy where SFRs are responsible for energy generation and ADS is essentially dedicated to minor actinide burning.

Concerning the economic analysis, compared to the reference scenario, the estimates show an average increase of LCOE of 20% for an SFR strategy over the whole period, and around 35% for the transmutation scenarios. It was also confirmed that the main contributor to the cost of electricity is the investment cost, responsible for 60–69% of the total cost. Results also show that the cost of the HLW disposal can be reduced by approximately a factor of 4 in a strategy using fast reactors and by a factor of 5 in a strategy using ADSs. The associated cost reduction, quite high in the absolute value, represents a relatively small value in LCOE compared to other contributions (1–3.7%). As it has been noted in several other studies, this is on account of the discount nature of LCOE.

The study in Section 3.3.1 (Summary of EU scenarios with transmutation option for nuclear phase out and continued nuclear scenarios) is a summary of the projects RED-IMPACT, PATEROS and ARCAS, completed within the EU Framework Programmes. This summary was prepared by the Belgian participants of the SYNERGIES project.

The RED-IMPACT project was to select representative fuel cycle scenarios to explore the impact of partitioning and transmutation technologies on the overall waste management, and specifically on a final high level repository. The PATEROS project had the objective of establishing a European vision for deployment of partitioning and transmutation of nuclear waste which can contribute to the deployment of sustainable nuclear energy. The ARCAS study aimed to compare ADSs and fast reactors as minor actinide burners both, as comes to their technology and economics.

In the addressed studies, a regional approach was adopted to implement the innovative fuel cycles associated with partitioning and transmutation in Europe addressing the impact of different strategies in various countries. Fast reactors and ADSs were considered for transuranic and minor actinide transmutation purposes.

The ADS type was found to be mostly adapted to minor actinides, and not transuranics, and thus more suited to a regional scenario in which different countries with different objectives share resources, facilities and spent fuel inventories in order to minimize wastes. The studies performed show that the full expected benefit of partitioning and transmutation related to bringing radiotoxicity of HLW below a natural uranium level in several hundreds of years and making the repository more compact can be realized only on a regional level (i.e. through cooperation of several interested counties). In the case of Europe, this conclusion applies to all 34 European countries no matter which nuclear energy policy an individual country might have.

The case study in Section 3.3.3 (Studies of minor actinide transmutation in SFRs) was conducted by participants from China, who performed comparative assessment of two fast reactor options to burn minor actinides produced by PWRs, one related to a transuranic fuelled SFR and another to a dedicated SFR burner. No ultimate winner was found; dedicated burner reactors are likely to have more safety related issues requiring further resolution, but they are more effective and could be deployed in relatively small numbers. The results suggest cooperative development and ownership of such potentially more expensive burner reactors may be of benefit.

3.5.4. Scenario family D

The case study in Section 3.4.1 (Evaluation of a scenario of transition to Th/^{233}U fuel cycle), conducted by participants from India, examined the potential of fast reactors with metallic fuel to speed up the buildup of fissile inventory needed for a transition to a thorium/^{233}U cycle. This study was bound to scenarios of the three stage Indian nuclear power programme aimed at efficient utilization of limited uranium and abundant thorium national resources:

- — Use of uranium based fuel for power generation primarily in PHWRs;
- — Introduction of high breeding ratio fast reactors using plutonium based fuel with depleted/reprocessed uranium in the blanket to increase the fissile inventory available for breeding ^{233}U;
- — Breeding of ^{233}U in fast reactor blankets and use of ^{233}U/thorium fuel in reactors in a self-sustainable manner.

With a link to this programme, the availability of technology for using metallic fuel in fast breeder reactors, along with its associated fuel cycle, is essential for building up necessary fissile inventory at a faster rate. The parametric studies performed assessed the availability of such technology and its impact on the time of transition to thorium/^{233}U fuel cycle. It was confirmed that fast reactors using metallic fuel can have a significant role in advancing the time period for transition to deployment of thorium/^{233}U based reactors. The study did not touch upon international cooperation, for example, to acquire additional fissile materials for a national fast reactor programme.

Section 3.4.2 (Summary of INPRO studies on global scenarios with introduction of Th) provides a short summary of the major findings of an IAEA publication [3.12]. The studies presented addressed three options of thorium introduction to nuclear energy:

- Once through fuel cycle with thermal reactors;
- Closed fuel cycle with thermal reactors;
- Closed fuel cycle with thermal and fast reactors.

The studies examined the potential to reduce enrichment requirements, reduce the production of plutonium and minor actinides, and increase the globally available fissile resources. They also examined fabrication and reprocessing capacities necessary for commercial utilization of thorium fuels and fuel cycles.

It is noted that many reactor types, including LWRs, HWRs, fast reactors, HTRs, MSBRs, can use thorium or ^{233}U as fuel with variable efficiency. The introduction of thorium to once through fuel cycles involving modern LWRs decreases plutonium and minor actinide content in the spent fuel. However, the enrichment and fuel fabrication costs are likely to increase. The introduction of thorium in a once through fuel cycle based on AHWRs can provide more advantages. The decrease of minor actinide production via thorium utilization only takes place when the designer succeeds in avoiding plutonium utilization in the thorium based fuel. For the once through cases, the higher burnup scenarios lead to a higher percentage of energy from thorium.

Thermal thorium reactors in a closed fuel cycle can provide approximately the same enhancements to uranium economy, enrichment and fuel manufacturing efforts as with use of uranium/plutonium MOX fuel. The study provides estimates for the levels of natural uranium costs at which thorium cycle can become competitive. It concludes that under some geographical and infrastructural conditions, the application of thorium may be considered as a complementary option for NESs with fast reactors in the uranium–plutonium fuel cycle.

3.6. CONCLUSIONS WITH RESPECT TO SYNERGIES PROJECT TASKS

3.6.1. Task 1: Evaluation of synergistic collaborative scenarios of fuel cycle infrastructure development

Proven workable options for synergistic collaboration between technology holders and users exist even for business as usual scenarios, employing thermal spectrum reactors in a once through fuel cycle, and scenarios with mono-recycling of uranium/plutonium in thermal spectrum reactors. The example is the EU commercial LWR spent fuel reprocessing and MOX fuel supply for a single recycle in LWRs. Currently, this type of collaboration is driven primarily by public acceptance concerns related to non-proliferation and security, environmental impact and footprint, among other things. An increase of natural uranium prices would increase the economic competitiveness of this option.

Some of the studies highlighted another possible near term synergy related to recycling of the reprocessed uranium from LWR spent fuel in HWRs. If realized, such an option, which has the potential to be competitive in the near term, could also boost plutonium recycling in MOX fuel, as plutonium is actually a by-product of uranium reprocessing.

Some participants from technology user and newcomer countries identified the medium term controlled dry storage of spent nuclear fuel to be the best choice given the current technology development and economic situation. In some cases, the countries had experience with vendors who took back the spent nuclear fuel for future reprocessing; however, the expediency of such an option is (and will be) conditioned by its competitiveness to other options, such as dry storage.

In the medium term, participants from some technology user countries are targeting regional solutions for spent fuel storage, as offering economic advantages through economy of scale factors and resource sharing. In the medium term, with the advent of a limited number of fast reactors in some technology holder countries, even broader opportunities for synergistic collaboration may arise, with regard to minimizing HLW subject to final disposal. Case studies on scenarios with the introduction of a number of fast reactors to support multi-recycling of plutonium in LWRs and fast reactors indicate that passing the plutonium from spent fuel of MOX fuelled LWRs through a fast reactor, or admixing the plutonium bred by a fast reactor to LWR spent fuel plutonium, opens the door to multi-recycling of plutonium in both, fast reactors and LWRs. This approach, which could rely only on proven near term technologies for both, fast reactors and LWRs, was shown to be quite effective in dealing with both current and legacy HLW from LWR spent nuclear fuel. The relevant scenarios are in good agreement with currently observed and projected developments, reflecting rather slow progress and notable uncertainty of fast reactor programmes in technology holder countries. Therefore, further investigation of the drivers and impediments for synergistic collaboration in such scenarios appears to be expedient.

Case studies on fast reactor centred scenarios, which are the scenarios with reprocessing of thermal reactor fuel to enable noticeable growth rate of fast reactor capacity, indicate that, in the longer term, implementation of large scale fast reactor programmes in just several technology holder countries may help, through synergistic collaboration with technology user and newcomer countries, to make a substantial move towards enhanced global sustainability of nuclear energy. The synergistic collaboration for these scenarios could be that technology user and newcomer countries send the spent nuclear fuel from their LWRs to technology holder countries, which reprocess it and use the recovered plutonium for the startup loads of fast reactors. Technology users and newcomers could then get back only the waste composed of fission products and minor actinides. As an option, they could also be supplied with MOX fuel for their LWRs.

Drivers supporting a potentially ‘win-win’ strategy for synergistic cooperation in such scenarios include the following:

- A potential to reverse progressive spent nuclear fuel and plutonium accumulation in storages;
- Savings of financial and manpower resources for users and newcomers to develop expensive national closed fuel cycle infrastructure while retaining all of the benefits of the closed nuclear fuel cycle;
- Expansion of nuclear energy business for the technology holders and associated economy of scale reductions in the cost of fuel cycle back end services for users — savings in the investments for closed fuel cycle infrastructure development of up to 50%;
- Substantial expansion of fissile resource for collaborating partners due to substitution of ^{235}U in UOX nuclear fuel of WWER type reactors by the plutonium separated from UOX spent nuclear fuel of WWER and used in MOX fuel of fast reactors;
- Concentration of sensitive reprocessing technologies just on a few sites to reduce proliferation resistance and security related concerns;
- A possibility to utilize cheaper categories of uranium (e.g. depleted or reprocessed uranium) for both users and technology holders.

Along with the drivers, the case studies on fast reactor centred scenarios have identified a number of possible impediments for synergistic collaboration, such as:

- Technical and institutional procedures related to nuclear fuel/HLW transactions that are not developed to sufficient detail;
- Non-transparent price formation for reprocessed spent fuel components and relevant fuel cycle services;
- Political and economic instability that may hamper cooperation among countries;
- National policies not supporting spent fuel reprocessing.

In this context, the issues requiring further investigation and clarification were found to be:

- Uncertainty of cost data for the fuel cycle stages, including transport;
- The still missing commonly accepted methodology to derive values of the spent fuel reprocessing products (e.g. regenerated uranium and plutonium);
- Missing data on timing of spent fuel deliveries, storage periods, conditions of reprocessing, and inventory of returned materials, among others.

A better understanding of these impediments and finding ways to overcome them in as near term as possible is crucially important to define and implement pathways to the long term globally sustainable NESs.

Some of the case studies performed suggest that synergistic collaboration might be considered on a cooperative international basis (e.g. regional fuel cycle centres). However, it is understood that first steps in this direction would involve cooperation among users and fuel cycle back end service providers. In the medium term, there are likely to be several such providers with a potential to ensure certain competition, and some studies indicate the number of such providers could increase in the future. Other studies indicate the benefits of synergistic collaboration show no sharp dependence on the shares of groups of countries with different policy regarding fuel cycle back end, they could be attained within reasonably broad variations of these shares.

Other case studies indicate synergy among fast and thermal reactors could play a positive role not only in scenarios with nuclear capacity growth, but also in the cases of scenarios with frozen or decreased nuclear capacity, including phase out scenarios. Synergistic collaboration among technology holder and user countries could also be of prime importance here, to secure sustainable capacity decrease or phase out with minimum HLW burden to future generations.

3.6.2. Task 2: Evaluation of additional options for nuclear energy systems with thermal and fast reactors

Programmes of heavy liquid metal cooled fast reactor development pursued in some countries in some cases suggest they should be started from enriched uranium rather that mixed uranium–plutonium based fuel. Such fast reactors are then viewed as an alternative to LWRs, rather than an addition to them. Although the uranium started heavy liquid metal cooled reactors are fissile self-sufficient and, in a closed nuclear fuel cycle, ensure natural uranium savings against LWRs operated once through, they are not designed to reduce legacy spent fuel generated from LWRs. A case study was performed that compared scenarios with different strategies of fast reactor startup (uranium–plutonium versus uranium load) and also considered variants of mixed deployment with different shares. It was found that:

- In the short and medium terms, the introduction of the enriched uranium startup load makes it possible to realize a high growth rate fast reactor deployment scenario under LWR reprocessing capacity limitations. The fleet of fast reactors in the case of a 100% fraction of the uranium startup load fast reactors could be increased by a factor of 1.5 compared to the case when all fast reactors start with MOX fuel obtained from the reprocessed LWR fuel.
- Options of fast reactor introduction with a share of uranium loaded fast reactors of up to 50%, the rest being MOX loaded fast reactors, show a positive effect with regard to the reduction of LWR spent fuel inventory, which could be reduced down to zero. Similar results are observed for the inventories of plutonium and minor actinides in long term storage facilities of LWR spent fuel.
- Use of enriched uranium for the first core load of a fast reactor requires more enrichment capacity.

The case studies performed by experts from countries with huge national nuclear demand and strong energy security considerations considered metallic fuelled SFRs with higher breeding ratios (~1.4) to speed up reaching the targeted overall capacity/structure/material balance of a national NES. The studies have proven high potential of the metallic fuelled SFR in achieving this goal, for the uranium–plutonium, as well as for the ^{233}U–thorium fuel cycle.

A case study was performed that included scenarios with fast reactors and supercritical parameter LWRs and some share of the SMRs and HTRs intended for co-generation and non-electrical applications, all in a closed nuclear fuel cycle. The study has shown that supercritical LWR with conversion ratio of about 0.8 coupled with the break-even fast reactors (breeding ratio of ~1.0) could meet the demands of a nuclear energy evolution scenario with 5000 GW(e) reached by 2100 in terms of natural uranium resources and HLWs. With regard to HTRs and SMRs, their inclusion in the system in reasonable numbers was shown not to downgrade significantly spent nuclear fuel reduction and fissile resource availability.

One of case studies summarized major findings of the INPRO activities accomplished previously for scenarios with ^{233}U/thorium fuel involvement in NESs. These studies have considered thorium incorporation in thermal reactors operating in a once through fuel cycle. It concluded that the introduction of thorium to once through fuel cycles involving modern LWRs decreases plutonium and minor actinide content in the spent fuel. However, the enrichment and fuel fabrication costs are likely to increase. The introduction of thorium in a once through fuel cycle based on AHWRs may provide more advantages. The decrease of minor actinide production via thorium utilization only takes place when the designer succeeds in avoiding plutonium use in the thorium based fuel.

The mentioned above study also addressed ‘traditional’ ways of thorium introduction to nuclear energy based on the application of fast reactors with thorium blankets to breed ^{233}U in a closed nuclear fuel cycle. It concluded that under some geographical and infrastructural conditions, the application of thorium may be considered as a complementary option for NESs with fast reactors in the uranium–plutonium fuel cycle.

3.6.3. Task 3: Evaluation of options for minor actinide management

The summaries of some previous studies performed in France and other EU Member States, prepared by SYNERGIES participants and included as case studies in this publication, provide some important insights on transmutability of particular elements and benefits and risks associated with minor actinide partitioning and transmutation, such as:

- Only the transmutation of all minor actinides, through multi-recycling operations in SFRs or ADSs, enables stabilization of their inventory over time.
- Scenarios involving the transmutation of all minor actinides are extremely impeded by the presence of curium and the implementation constraints often exceed that of the scenarios, in which only americium is transmuted, by one order of magnitude. With this in view, long term controlled storage of curium could be the preferable option.
- The transmutation of americium (or all minor actinides) would result in a reduction by a factor of up to 7.3 (americium) to 9.8 (all minor actinides) of the footprint of the HLW disposal zone after an interim storage period of 120 years. However, a total reduction of the repository footprint taking into account ILW, LLW and common infrastructures would be only by a factor of 3. The associated cost reduction in terms of the LCOE is evaluated in some studies at 1–3.7%, which, owing to the discounted nature of LCOE, is not representative of the huge absolute costs that could potentially be saved by future generations.
- In transmutation options, higher contents of minor actinides at the fuel manufacturing and processing steps will require significant design modifications for dealing with obvious thermal and radiation protection problems. The complexity of the operations carried out during the operation phase (loading/unloading, interim waste storage, and transport) will also be increased.
- Some economic studies show that the cost increase related to the transmutation process could vary between 5–9% in the case of SFRs and 26% in the case of ADSs. Other studies indicate these figures could be 20% and 35%, respectively. It was noted that towards the lower end of this increase other factors, such as better public acceptance of scenarios with minimized long lived radiotoxic waste, could probably, outweigh the economic losses in decision making.

To minimize risks, the introduction of transmutation could follow a step by step approach, for example, starting with options not affecting much the reactor safety and economics, such as adding minor actinides to fast reactor blankets.

Some of the case studies examined, on a comparative basis, the potential of both SFRs and ADSs to shoulder the transmutation function. The ADSs were found to be more effective (their required number could therefore be relatively small) — although, with a high probability, more expensive. The conclusion was ADSs could be viewed more like a regional solution, to be jointly developed and operated by several countries to cater to each country’s needs, including the needs of the countries phasing out nuclear power. It was found that ADSs are more suited to minor actinide transmutation, while transuranics could be effectively recycled in SFRs.

Some of the case studies analysed, on a comparative basis, two fast reactor options to transmute minor actinides, one related to transuranic fuelled SFR and another to a dedicated SFR burner. No ultimate winner was found: dedicated burner reactors are likely to have more safety related issues requiring further resolution, but they are more effective and could be deployed in relatively small numbers. Looking at the results of this study one can implicitly suggest cooperative development and ownership of such potentially more expensive burner reactors might be of benefit, similar to the ADS case.

3.6.4. Task 4: Elaboration of key indicators specific for synergistic collaboration, including economic assessment methods

The case studies performed used different sets of key indicators for the scenario analysis. Appendix I summarizes the indicators used and includes a table with the cumulative key indicator set, which is then compared to the GAINS metrics [3.69]. The overall consistency of the GAINS key indicator set was confirmed with only minor deviations, as discussed in Appendix I.

A database of best estimate economic characteristics of each fuel cycle step and each LUEC component of nuclear reactors has been developed and is presented in Appendix II. The data are provided as ranges (minimum and maximum) with the best estimate value, and also include the economy of scale curves for enrichment and reprocessing facilities. The database is being periodically updated used in all studies performed under INPRO Task 1, on global scenarios, to which the SYNERGIES collaborative project belongs.

Some of the case studies provided evaluations of absolute costs needed to develop and implement advanced technologies for fuel cycle back end, such as reprocessing, and this cost could amount to a few tens of billions of US dollars for a complete fuel cycle back end enterprise with reprocessing and fuel fabrication from reprocessed material. Collaborative solutions that result in centralization of the back end fuel cycle services could help to reduce the required investments by up to 50%. However, the developments being in the medium and long term, the scale of these changes that would make a difference to future generations is not brought to light adequately through traditional economic indicators, such as the LUEC, owing to the discount rate being incorporated. Cash flow analysis could then be recommended to amend LUEC to arrive at a real scale of problems that future generations may face owing to the decisions made today.

One of the case studies compared the results of a scenario study with the introduction of ALWR with a single MOX recycle in heterogeneous and homogeneous world models. The conclusion is the heterogeneous model could provide more realistic and more correct results with respect to the ALWR MOX share, the required reprocessing capacity and HLW volume reduction.

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4. NEAR AND MEDIUM TERM ACTIONS TO ENSURE LONG TERM SUSTAINABILITY OF NUCLEAR ENERGY SYSTEMS

Near and medium term actions are needed to continue to ensure and improve the longer term sustainability of global nuclear energy. These actions can be grouped into several areas, including technology development, infrastructure development, institutional development and international cooperation. Technology development is primarily needed to advance innovative technologies that are not yet available at a technical maturity to support industrial scale deployment. Institutional development is used broadly here to include the establishment of personnel training, regulatory agencies, trade agreements and legal authority, among other things. International cooperation could help to expand the benefits of innovative technologies to those users who have no plans to deploy them domestically.

4.1. BACKGROUND

This publication has explored a number of approaches to improving nuclear energy sustainability on a local, regional and global scale. Many of these approaches involved synergistic activities that increased the overall sustainability of the nuclear energy systems (NESs) of the parties involved by reducing the cost of nuclear energy, improving waste management, reducing natural resource usage or otherwise improving the efficiency of the combined nuclear systems. While innovative NESs is a theme in many of the case studies, many others involve application of existing technologies and synergies with new parties or on a wider scale.

The basic concept of Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES) with respect to sustainability is to have the whole achieve more than the parts. If one partner in a synergistic collaboration is achieving enhanced sustainability, then the other partner may achieve the same enhancement without the requisite investment in technologies and the related infrastructure. This is already the normal mode of operation at the front end of the fuel cycle for many nuclear programmes, where services are provided through multiple bilateral and multilateral agreements. Given the economies of scale, it is usually more economical to have a few large regional facilities performing conversion, enrichment and fuel fabrication than for each country to develop its own smaller facilities. Fewer facilities in fewer countries can also have positive impacts on sustainability in the areas of infrastructure, physical protection and, for enrichment and reprocessing, on proliferation resistance.

The potential for significant sustainability enhancements also exists in other parts of the NES. These potential enhancements require development of technologies and construction and operation of new infrastructure. As with the front end, limiting the number of facilities and employing synergies can have positive benefits through, for example, the transfer of spent fuel for reprocessing or disposal or the transfer of minor actinides for transmutation. The impacts can be positive for both parties, as the suppliers can achieve improved economies of scale and recycle the materials after reprocessing in their national nuclear programmes, while the user can avoid costly research and capital investments. Thus, synergies in new reactor technologies and back end services would support faster progress in increasing global NES sustainability while individual programmes proceed at their own pace.

Referring to the options for enhanced nuclear energy sustainability outlined in Section 2 and presented in detail in Appendix V, the most commonly used today is Option A (once through nuclear fuel cycle), as based on a once through nuclear fuel cycle and nuclear power plants with thermal spectrum reactors used to generate electricity. Most nuclear programmes currently involve some level of synergism with other countries at the front end of the nuclear fuel cycle, through well established supply services for natural uranium and enrichment services and in the area of fuel fabrication, all governed by bilateral and, in a few cases, multilateral agreements among countries. Through bilateral agreements with supplier States, newcomers to nuclear energy can benefit from similar and other synergistic interactions with existing programmes to establish the necessary fuel cycle and institutional functions needed for Option A, including the fuel cycle front end and back end, as well as the legal, regulatory and other institutional activities needed for operation of nuclear power plants.

Option A includes planning for ultimate end state of each waste stream, while Option F (final geological disposal of all wastes) adds implementation of waste disposal. At this time, no nuclear programmes have implemented Option F, as no geological repositories are in operation for civilian spent nuclear fuel or high level waste. The first such repository could appear in Finland around 2020.[1] A number of geologies may be acceptable for repositories, and larger countries with multiple geological regions might find multiple acceptable sites. However, smaller countries or countries with limited geological diversity could have some difficulty in locating domestic sites and would therefore benefit from synergies such as regional disposal.[2] The agreements to enable these will require significant development in the political and legal and institutional areas [4.1]. Geological disposal is a prerequisite for achievement of a complete nuclear fuel cycle, as all nuclear fuel cycles generate some ultimate long lived radioactive waste that requires geological isolation.

Option A may also include higher reactor outlet temperatures, which reduces water usage by generating more net electricity from the same amount of gross heat generation. This option could also expand the application of nuclear energy to additional markets beyond electricity[3], but the impact on economics will not be clear until the cost of the associated technologies is better understood. The opportunities for synergies within this option are primarily from deployment of new reactor designs in countries other than the country of origin.

In at least one case belonging to sustainability Option A, which is the Indian advanced heavy water reactor, planned to be constructed by 2020, the provisions are made for ^{233}U to be bred and burned in situ within the heterogeneous core with enriched uranium or plutonium based seed fuel, in a once through nuclear fuel cycle [4.2]. Realization of such option would ensure certain savings of natural uranium, but requires alternative fuel cycle infrastructure development for both fuel cycle front end and back end.

The emerging concepts of other breed and burn reactors[4] also belong to sustainability Option A. When and if realized, they could secure savings in natural fissile resource and the reduced specific high level waste, achieved through very high burnups of fuel in a once through fuel cycle. However, practical realization of such concepts would require development of the fuel and structural materials for very high burnups and fast neutron fluences. At present, it is not clear whether such materials and fuels could at all be developed, which makes technology development along this trend very risky. The economic characteristics of breed and burn reactors, which are at very early development stages, also remain unclear.

Options B (recycling of spent fuel with only physical processing), C (limited recycling of spent fuel), and D (complete recycling of spent fuel) provide improvements in resource utilization (part of the International Project on Innovative Nuclear Reactors and Fuel Cycles, INPRO, environment area) and waste management, and could also provide additional environmental benefits related to reduction of land use for mining and waste disposal. All of these options involve improvements in the use of fissile materials created in the reactors through some level of fuel recycling instead of treating them as waste.[5] All of these options also require the development or deployment of advanced technologies for reactors and fuels, and reprocessing and waste forms for the recycle options. The impacts on economics, infrastructure, safety, physical protection and proliferation resistance will depend on the specific technologies and operational procedures employed. Care needs to be taken while pursuing enhanced sustainability in the waste management and environment areas to ensure that performance does not fall below the minimum thresholds for sustainability in the other areas.

It should be noted that many of the reactors mentioned above in conjunction with Option A (once through nuclear fuel cycle) could also be considered for operation in a closed fuel cycle, as per Options B (recycling of spent fuel with only physical processing), C (limited recycling of spent fuel) and D (complete recycling of spent fuel).

Several programmes have achieved Option C (limited recycling of spent fuel) at an industrial scale with the mono-recycling of plutonium–mixed oxide or uranium oxide in light water reactors. A number of the programmes accomplished this through synergistic activities without developing and deploying all of the necessary technologies domestically. In particular, several countries without spent fuel reprocessing or mixed oxide fuel fabrication

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[1] For example, see www.world-nuclear-news.org/WR-Licence-granted-for-Finnish-used-fuel-repository-1211155.html and www.world-nuclear-news.org/WR-Finnish-regulator-approves-Posivas-waste-repository-plan-12021501.html

[2] See www.nrc.gov/waste/llw-disposal/licensing/compacts.html

[3] The markets for non-electrical applications, such as nuclear heat based hydrogen production, have not yet emerged at the time this publication was prepared.

[4] For example, see www2.technologyreview.com/news/412188/tr10-traveling-wave-reactor

[5] The 'breed and burn' option in a once through nuclear fuel cycle, corresponding to sustainability Option A (once through nuclear fuel cycle), might help to achieve some benefits similar to those of Option C (limited recycling of spent fuel); however, as already mentioned, the technologies under this option are still at an early development stage (with the exception of the Indian advanced heavy water reactor).

capabilities contracted for these services. Thus, not only have the Option C technologies been developed and deployed on a commercial scale, but also the institutional mechanisms have been established and successfully used to extend the use of these facilities to other countries.

With regard to Option B (recycle of spent fuel with only physical processing), a substantial amount of research has been carried out enabling mono-recycling of light water reactor spent fuel in heavy water reactors, but this option has so far not been implemented. The benefits that could be achieved with this option are generally similar to those of Option C (limited recycling of spent fuel), plus it completely avoids proliferation sensitive chemical reprocessing technologies.

Option C (limited recycling of spent fuel) establishes many of the technologies and institutional mechanisms needed for full recycle in Option D (complete recycle of spent fuel). No programme has so far commercially employed Option D with fast reactors and a closed fuel cycle, but several Member States are conducting necessary research, much of which involves international R&D collaboration. Moreover, some Member States already have certain historical experience in limited scale demonstration of Option D on a national level. More recently, progress is being made in a scaled up demonstration of fast spectrum reactors in China, India and the Russian Federation, with plans to achieve Option D commercially within the next decade.

Option D (complete recycle of spent fuel) can also include thorium based closed fuel cycle. Current development is primarily in countries with large thorium resources, limited uranium resources and growing nuclear programmes, with India the prime example. India already has an experience of ^{233}U breeding from thorium and ^{233}U–thorium fuel production and use in the experimental KAMINI (Kalpakkam Mini) reactor. As already mentioned, India is also considering the introduction of thorium within a once through fuel cycle, in a ‘breed and burn’ mode, within the heterogeneous advanced heavy water reactor core.

Option E (minor actinide or minor actinides and fission products transmutation) has so far not been achieved on a commercial scale, but key research on partitioning and transmutation of minor actinides is under way. Progress is also being made in transmutation fuel development for fast reactors and in the development of accelerator driven systems. Some Member States have determined that minor actinide management is necessary to achieve their waste management goals (see Annex XXIV), while others have not determined if the additional benefits are worth the additional costs (see Annex XXVI), or suggest only partial minor actinide transmutation (see Annex IV).

4.2. TECHNOLOGY DEVELOPMENT

Many of the options for improving sustainability require development of advanced technologies or improvements in technologies that have seen only limited deployment. Near and medium term actions for technology development are focused on developing and demonstrating enabling technologies for the sustainability enhancement options. Individual Member States will proceed at their own pace with respect to research on these technologies. Most of the larger or longer established national programmes are working on research related to one or more of the sustainability options, based on national priorities. The key technologies and R&D include:

- Irradiated material shipping and storage methods;
- Geological repository research and engineered barriers development;
- Spent fuel reprocessing;
- Reprocessing off-gas management;
- Mixed oxide and dense (metallic and nitride) fuels development;
- Fast spectrum reactor development;
- Fissile materials production;
- Minor actinides separations;
- Remote fuel fabrication techniques;
- Advanced transmutation;
- Thorium fuel cycle technologies.

The maturation of these technologies in the near and medium terms will help to improve sustainability in the longer term, even if the technology holders only use them for domestic programmes. Use of these technologies in synergistic activities to assist other less developed programmes would further advance global sustainability. A key challenge for all advanced nuclear technologies is to improve economic performance. More information on the current research programmes can be found in Refs [4.3–4.14].

While technology R&D enables improvements in sustainability, it does not achieve any advancement in sustainability unless and until it proceeds to deployment. The scale of deployment is then the primary driver behind the scale of benefits realized. At present, widespread deployment of reactors and front end fuel cycle facilities exist along with more limited deployment of reprocessing and mixed oxide fuel fabrication.

Looking forward to managing growing spent nuclear fuel inventories in the near to medium term, geological repositories need to be opened for spent nuclear fuel disposal or reprocessing capacities need to be expanded and geological repositories opened for disposal of high level waste. Either option will allow for reductions in spent nuclear fuel inventories while providing a waste solution missing from today's NES. The practice of indefinite storage of uranium oxide spent nuclear fuel, light water reactor–mixed oxide spent nuclear fuel and high level waste is not sustainable because, by passing problems created by the current generation to future generations, it violates the basic tenant of sustainability of "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [4.15].

The deployment of geological repositories has been primarily driven by social and political considerations, with technical considerations secondary and costs being a result rather than a driver. The successful opening and operation of one or more repositories is likely to reduce public uncertainties about nuclear waste and improve the associated social attitudes concerning specific repository projects, enabling more rapid deployment later, including potentially the deployment of regional repositories accepting waste from multiple countries. Depending on waste acceptance criteria and the safeguards and security requirements to final disposal of waste, the startup of repositories may also influence decisions on direct disposal versus reprocessing of spent nuclear fuel.

In the medium term, initial deployment of fast spectrum reactors is anticipated. This initial deployment may serve multiple purposes. First, it will help to reduce the technical risk associated with industrial scale application of these technologies. Second, experience in the construction and operation of a limited number of fast reactors will provide important lessons prior to a more rapid expansion of reactors later in support of scenarios of the C family (see Section 2.7.4). Third, the initial facilities will help to answer questions about the true cost of fast reactors, reducing the economic uncertainties and enabling better analyses of the costs and benefits of transition to closed fuel cycles.

4.3. INSTITUTIONAL DEVELOPMENT

A number of institutional developments could help to encourage more synergies on NESs that would lead to more effective management and operations of nuclear systems and potentially to higher utilization of nuclear fuel cycle facilities. These efficiencies would in turn result in improved economics of NESs. Many are in the areas of cooperation on planning and personnel development that require limited investments. Others are related to nuclear facilities and management of materials and wastes.

The results of the INPRO Dialogue Forum on drivers and impediments for regional cooperation on the way to sustainable NESs included a number of areas where cooperation already exists and can be expanded, as well as areas where cooperation is limited or missing.[6] Appendix IV discusses the major findings.

Nuclear energy is most economical when larger reactors are operating at full power. Smaller markets and markets with limited grid capacity might not be able to support this level of power production. Improvements in regional energy planning would help to better define the needs for large production facilities, including consideration for grid upgrades to enable export of excess electricity production. Such planning would be especially helpful for newcomer countries as part of the decision process for their first reactors.

Both newcomer countries and countries with existing programmes can benefit from expertise and information sharing on licensing, regulations, radioprotection and environmental impact assessment, among other things. Some international organizations already exist in these areas, such as the World Association of Nuclear Operators and the European Nuclear Safety Regulators Group. Additional regional organizations should be developed. Beyond information sharing, joint support for, and sharing of, emergency infrastructure would also improve overall safety while reducing costs.

[6] See www.iaea.org/INPRO/4th_Dialogue_Forum/index.html

Sharing human resources and expertise can extend beyond regulations and safety to include routine operations. Specific skills are needed during refuelling outages for routine maintenance and refuelling activities. Regional teams that move from reactor to reactor could improve execution of refuelling activities, reducing downtime while also accomplishing more maintenance during the outages. Such teams would be more experienced and provide more consistency in refuelling planning and execution.

While the IAEA International Safeguards programme can provide assurances to the world of the peaceful intent of nuclear energy users, regional groups such as the Brazilian–Argentine Agency for Accounting and Control of Nuclear Materials can also improve trust and foster cooperation. Such cooperation can lead to joint R&D and even to joint ownership and sharing of facilities. In many cases, the financial driver for economies of scale of fuel cycle facilities can only be achieved through cooperative agreements.

The history of back end cooperative agreements has primarily involved one party developing reprocessing capacity for domestic purposes that was occasionally idle, and selling services to other parties to fill in during slow periods in their domestic programmes. France has established commercial reprocessing of light water reactor spent nuclear fuel and provides relevant services with the supply of the mixed oxide fuel and return of vitrified high level waste to a number of countries. A similar mode of cooperation was spawned with the end of the Soviet Union, where some movement of spent fuel for storage or recycle changed from a domestic activity to an international activity[7]. These historic and ongoing activities have resulted in the establishment of important institutional mechanisms to support the transfer of irradiated materials between countries, a key enabler for further expansion of cooperative synergistic activities. These mechanisms need to be examined to ensure they will remain sufficient assuming a substantial expansion in the international transfer of spent fuels, reconstituted fresh fuels and waste materials.

The current practice for spent nuclear fuel management in most countries[8] with NESs is interim storage pending development of geological repositories. This practice includes transition from wet storage to dry storage as the spent nuclear fuel cools if wet storage capacity is limited. Dry storage technology is modular and can be implemented at any scale without significant differences in unit costs. Some countries may find it advantageous instead of contracting for interim storage, especially if it involves transfer of ownership/management responsibility of the fuel. This is an area where additional legal and regulatory evolution would be beneficial to help transition from a limited number of bilateral agreements to a set of international standards and practices.

One issue with interim storage is the lack of financial incentive to move on to a more permanent solution. Technology exists to enable storage over at least 50 years.[9] Standard economic treatment of net present value and discounting consistently shows the cost of long term interim storage is minimal and the larger disposal investments cost less if postponed. Because disposal costs are incurred in the near term but the benefits are distributed over very long time horizons, the standard application of discounting reduces values far into the future to essentially zero in present day terms. Needless to say, such an approach fails to address the intergenerational aspect of sustainability. To avoid it, one is free to choose the right discount rate, including a zero discount rate if that is the perception about the future value of the cost and benefits.

This issue of discounting over intergenerational timeframes is not unique to analysis of investments in NESs, but is also a topic in the climate change community [4.16], where again the costs occur in the nearer term while the benefits (or avoidance of negative outcomes) do not occur for often a century or more. With respect to this, some countries have adopted a policy of declining discount rates to address the impact of discounting on economic analyses of long term investments [4.17, 4.18]. Non-discounted cash flow analysis, as a supplement to the discounted levelized unit energy cost, could also be applied for this purpose (see Section 3).

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[7] The former Soviet Union also practised (and the Russian Federation continues to practise) this with several Eastern European countries, which was international from the outset.

[8] A limited number of countries recycle first generation spent fuel but store the second generation spent mixed oxide fuel. This is effectively a consolidation strategy pending development and deployment of the technologies needed to transition to a closed fuel cycle.

[9] It is noted that, though manufacturers of dry storage casks claim their integrity for up to 100 years, the long term integrity of fuel within such casks remain unproven (see Section 2).

4.4. ROADMAPPING TOWARDS SUSTAINABLE NUCLEAR ENERGY

All of the areas previously discussed in this section can benefit from collaboration and the resulting synergies. Collaborating countries, in turn, can benefit from sharing of nuclear energy planning which can provide information on the projected size and timing for R&D and infrastructure deployment and demonstrate the looming needs for institutional developments.

Plans and projections are not guarantees that research will be successful or that development will occur on schedule. However, they do provide a vision of what is being attempted. When such visions are shared, groups can work together or independently to achieve those visions. Either approach increases the probability a vision will be realized. The large size and complicated nature of NESs require significant human and capital resources be applied in multiple areas simultaneously. Shared visions can help to coordinate these efforts by providing a roadmap for many (or for all) to follow. The more countries that are willing to share their plans and projections, the better the research, equipment, training and other providers can plan their own efforts. This can improve the overall efficiency of all parts of the global system.

In the near term, general roadmaps on the timing of nuclear reactor deployments can provide a starting point by indicating the level of construction services and fuel cycle services needed. Related workforce training, fuel cycle infrastructure development and other needs can then be developed. When these plans include newcomer countries, the related development on institutional mechanisms, such as regulatory agencies, can better be assisted. When the plans include assumptions about services such as fuel lease/take back, then potential service providers can better develop their own business plans, and improved institutional measures can be developed in advance of the need for their application. When these roadmaps include advanced reactors and advanced fuel cycles, they can also provide the basis for R&D roadmaps, which themselves can help to catalyse development of shared research facilities.

Many plans are already shared, but there has not been an effort to collect and integrate these plans into a global shared vision. Due to the cascading impact of a shared nuclear infrastructure development plan, a nuclear roadmapping effort could be recommended as one of the first near term activities.

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5. FINDINGS AND CONCLUSIONS OF THE SYNERGIES COLLABORATIVE PROJECT

To address challenges and to enhance sustainability, the global nuclear energy system (NES) has to incorporate innovations in technological and institutional areas. Synergies among the various existing and innovative nuclear energy technologies and options to amplify them through synergistic collaboration among countries towards sustainable nuclear energy were examined in the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) collaborative project on Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES). Experts from Algeria, Argentina, Armenia, Belgium, Bulgaria, Canada, China, France, India, Indonesia, Israel, Italy, Japan, the Republic of Korea, Malaysia, the OECD Nuclear Energy Agency, Pakistan, Romania, Poland, the Russian Federation, Spain, Ukraine, the United States of America and Viet Nam were participants or observers in different project tasks. To achieve the project objectives, twenty seven case studies were carried out, which are summarized in Section 3. Major findings and conclusions of the project are summarized in the following sections.

5.1. CASE STUDIES

The case studies performed within the SYNERGIES collaborative project show growing interest of Member States in longer term analysis of nuclear energy evolution scenarios taking into account synergies among the various technologies and options for cooperation in nuclear fuel cycle that may help to enhance nuclear energy sustainability on a national, regional and global level. The twenty seven case studies were performed within the project. The synergistic approaches were considered as instruments to meet challenges of the current NESs. Participants of the project have discussed drivers and impediments of the approaches gained from their experience and presented their visions on enhancing sustainability of future NESs.

5.1.1. Support of national R&D and deployment programmes by regional and interregional cooperation

Several case studies of the project showed examples of regional and interregional support to implementation of national programmes of nuclear power development and deployment.

The case study from Armenia assessed implementation of an approach aimed at the minimization of R&D programmes and development of nuclear fuel cycle. The Armenian nuclear power plants with reactor units of the light water reactor (LWR) type successfully operates in the open nuclear fuel cycle generating competitive electricity with a minimal nuclear fuel cycle infrastructure. Both the reactor design and front end nuclear fuel cycle services are supplied from abroad. This type of cooperation model may be applicable to many countries with small nuclear programmes, especially to the newcomers.

The studies from Argentina, Romania and Ukraine addressed a model of development in which execution of domestic R&D programmes is supported by international cooperation that accelerates implementation of the national deployment strategies and provides an opportunity to take part in international R&D projects aimed at solving long term problems in enhancing sustainability of nuclear power. The countries of the group have demonstrated some common approaches to regional and interregional cooperation. They look for an optimal balance between their own capabilities and capabilities provided by external suppliers. Public opinion in the countries supports further deployment of nuclear power. The governments consider nuclear power as a stable component of the national energy mix taking into consideration security of supply, reliability, economic efficiency and low greenhouse gas emissions. All countries from this group use and intend to use in the future nuclear power plants of foreign designs. They consider regional solutions for spent fuel repository as a promising development. Specialists from research institutes of the countries evaluate reactor designs offered by external suppliers and those under development, including Generation IV systems, with an aim of identifying the systems of most interest.

Along with the commonalities, case studies of the group have demonstrated some specific features. Argentina that currently has productive capacities of all the stages of the once through nuclear fuel cycle plans to become a regional supplier in Latin America and even a global supplier with small reactors of Argentinian design. Romania fabricates the nuclear fuel for the Canada deuterium–uranium reactors by using domestic uranium reserves.

Presently, Indonesia has no nuclear power, yet it intends to deploy its first nuclear power plants based on foreign designs, while continuing with domestic R&D programmes. The Indonesian study considers a once through uranium oxide fuel cycle with pressurized water reactors as the most viable option for the country until the middle of the 21st century, while examining a number of fuel cycle options for the future, including a closed nuclear fuel cycle with fast reactors, mixed oxide (MOX) recycle in LWRs and the uranium–thorium fuel cycle.

5.1.2. Regional collaboration

Three case studies of the report addressed the issues related to sustainability enhancement of several national NESs within steady regional cooperation. The study on EU27 scenarios with the extended use of regional fuel cycle centre consisting of the La Hague and MELOX facilities demonstrated proven options for synergistic collaboration between nine EU Member States, such as the limited LWR spent fuel reprocessing and MOX fuel supply for a single recycle in LWRs. The study presents important considerations that are the main drivers for such services. They are related to risk reduction with respect to non-proliferation and security, nuclear safety, environmental impact and footprint and public acceptance. They also help to improve NES performance to provide increased energy independence, optimized cost of nuclear electricity, preservation of natural resources through a 10–15% reduction in natural uranium consumption and minimization of generated waste and deep geological disposal requirements. Altogether, these factors could outweigh the associated slight increase of fuel costs. The increase of natural uranium price will naturally make this option more economically attractive.

The study of experts from Armenia, Belarus, the Russian Federation and Ukraine also analysed the issues of regional collaboration. Previous cooperation on the deployment and operation of water cooled, water moderated power reactors (WWERs) of the LWR type was a starting point of the study. In the heterogeneous model developed in the study, the LWR reactor fleet was supplemented by introduction of fast reactors with an aim to evaluate the future prospects. The study has concluded that collaboration at fuel cycle back end is likely an inevitable solution on the path towards regionally and globally sustainable nuclear power. The following drivers for ‘win-win’ cooperation were identified:

— Exclusion of accumulation of spent (used) nuclear fuel and plutonium therein;
— Substantial reduction of uranium consumption (by a factor of 10 and more);
— Use of cheaper categories of uranium;
— Savings of financial and human resources for the user countries;
— Expansion of nuclear energy business for the technology holders.

Along with the drivers, impediments for the collaboration were found: technical and institutional contexts are not yet sufficiently developed; the price formation is not transparent; and the motivations for collaboration in the fuel cycle back end are not always evident because of uncertainty of the input data and rules.

Participants from Italy investigated scenarios involving cooperation among a country that on a national level has adopted a nuclear phase out strategy and other countries in the region potentially interested in introduction or expansion of their nuclear energy programmes [5.1]. Italy is taken as an example of a country that has adopted a nuclear moratorium but keeps national utility operating several thermal reactors abroad and also maintains its research and development programmes, including experimental facilities. To justify potential interest of other countries in the region to initiate or expand their nuclear energy programmes according to the scenarios considered, two factors are said to be contributing, which are progress in the buildup of a European system of interconnected electrical grids allowing for high voltage transmissions and introduction of constraints on emissions of greenhouse gases, first of all, carbon based. The idea behind the considered scenarios is that a country that cannot build or maintain nuclear power plants on its own territory could do so abroad and then benefit from importing the baseload electricity from these other countries under the corresponding agreements and contracts. Specifically, this study examined positive economic effects from centralization of the front and back end fuel cycle services. Compared to national deployments, such centralization could yield a reduction of nuclear fuel costs by around 35–50%.

5.1.3. Technical synergies aimed at plutonium utilization

Case studies from China, France, Japan, the Russian Federation, Ukraine and the study jointly implemented by the IAEA and participants from the Russian Federation have shown a potential of the technical synergies aimed at plutonium utilization.

All these studies emphasize the potential of international cooperation in fuel cycle back end as a sustainable approach to involving the innovative components to the current NESs. There are several drivers indicated in all six studies that motivate developments in this scientific and technical area. The NESs based on technical synergies provide an opportunity to stop further accumulation of used nuclear fuel from pressurized water reactors and plutonium therein or even to decrease the amount of plutonium to operational needs, with minimum storage capacities and minimal quantities of actinides accumulated during storage of LWR used nuclear fuel. The demand for natural uranium in the LWR/fast reactor plutonium balanced NES can be reduced by a half in case of stabilized nuclear energy demand or reduced up to 100 times in case of high energy demand and high share of fast reactors in the system. Exclusion of excessive plutonium accumulation would facilitate safeguard procedures in fuel cycle back end and, in this way, strengthen the non-proliferation regime. Absence of perceptible quantities of plutonium in radioactive waste is also a significant advantage from the standpoint of environmental impact.

Along with the drivers, several impediments were noted in different case studies. Among them are a low pace of the LWR MOX and especially fast reactor MOX technologies development and industrial deployment, present day availability of large and rather cheap natural uranium reserves, high anticipated costs of fast reactor construction, used fuel reprocessing and MOX fuel fabrication.

Scenarios with multi-recycling of plutonium in LWRs and fast reactors examined in France and the Russian Federation explored the options for utilization of the plutonium from spent MOX fuel that is not possible in the once through nuclear fuel cycle. They emphasized flexibility of the LWR/fast reactor system capable to provide the balance of plutonium production and consumption for both, the case of rather high nuclear electricity demand and for the case of the demand stabilization.

Preliminary analysis of the nuclear energy development scenarios based on uranium–plutonium multi-recycling in China examined the potential of indigenously developed sodium cooled fast reactors (SFRs) to meet high national nuclear energy demand targets in the short and medium term. It was shown that meeting the challenging 2030 target requires conducting the RD&D, and implementing the metal fuelled SFR with a breeding ratio of above 1.4, as well as advanced reprocessing technologies.

Long term scenario study for nuclear fuel cycle in Japan investigated the possible role of fast reactors and closed nuclear fuel cycles in three national scenarios representing a reduction of the role of nuclear energy in the national energy mix, as a follow-up case study to energy policy change following the Tokyo Electric Power Company's Fukushima Daiichi nuclear accident, in 2011. It was concluded that advantages of the full reprocessing strategy compared to direct disposal strategy and the partial reprocessing are observed in all considered scenarios. The study is a good illustration of a positive role that fast reactors and closed nuclear fuel cycles could play in the nuclear phase out and no growth scenarios. Their capacity being in place, they could also provide back end services to other countries, such as for example, MOX fuel supply for use in LWRs.

The main objective of the case study from Ukraine was to evaluate LWR (WWER) fast reactor scenarios as a pathway to decrease spent (used) accumulation. Heavy water reactors (HWRs) operated on reprocessed uranium from LWR used fuel were also included into the model of a national NES. In the medium term, the closed nuclear fuel cycle based on fast reactors was found to be economically unattractive in Ukraine, on account of the impediments mentioned above. More attractive appeared to be a once through fuel cycle based on HWRs fed with regenerated uranium. As limitations on used fuel accumulation arise in a longer term perspective, the introduction of fast reactors, LWR MOX and the related nuclear fuel cycles might become reasonable.

The issues of interregional cooperation based on future LWR/fast reactor NESs were considered in the study done jointly by the IAEA and the participants of the project from the Russian Federation. The heterogeneous world model and global scenarios developed in the GAINS project were used in the study. It was assumed that commissioning of the LWR MOX/fast reactor systems should be expected at first in a few countries mastering these technologies. Then used fuel from LWRs of newcomer countries could be sent to technology holder countries for reprocessing and fabrication of the MOX fuel which could be used in both countries (for fast reactors in technology holder countries and for LWRs in newcomer countries). Here interregional cooperation could make the advantages of the LWR/fast reactor NES available and affordable to a wide range of nuclear power countries, including the newcomers.

5.1.4. Technical synergies aimed at enhanced waste management

A group of case studies from Belgium, Canada, China, France, Spain and the European Union was dedicated to the analysis of the technical synergy potential with regard to waste management.

The two case studies from Canada considered options on recycling reprocessed uranium from LWR in pressurized HWRs and a scenario analysis of reburning LWR americium in HWRs. The study on recycling reprocessed uranium in HWRs provided an estimate of the economic savings for HWR utility from reprocessed uranium use compared to natural uranium use under certain assumptions with regard to natural uranium and reprocessing costs. The scenario analysis of reburning LWR americium in HWRs showed the reduction of requirements to high level waste (HLW) disposal and provided an estimate of possible economic benefits to HWR utility depending on disposal costs, partitioning costs and natural uranium price.

The objective of the French study on radioactive waste transmutation options was to obtain an assessment of industrial perspectives on partitioning and transmutation of long lived elements. The research was based on the analysis of technical and economic scenarios taking into account the possibilities of optimization between long lived HLW transmutation processes, their interim storage and their disposal in a geological repository. With SFR deployment considered in France for 2040, the study investigated six scenarios. In all of them, plutonium recycling in SFR was assumed while approaches to minor actinide management were different.

There have been several major findings in the study. The transmutation of minor actinides significantly reduces their inventory in the geological repository; however, the minor actinide inventory in the reactors and plants increases. Only the transmutation of all minor actinides enables stabilization of their inventory over time. The transmutation of americium and minor actinides would result in a reduction by a factor up to 7.3 and 9.8, respectively, of the footprint of the HLW disposal zone after an interim storage period of 120 years. In transmutation options, higher contents of minor actinides at the fuel manufacturing and processing steps will require significant design modifications for dealing with obvious thermal and radiation protection problems. The complexity of the operations carried out during the operating phase (loading/unloading, interim waste storage and transport) will also increase. Scenarios involving the transmutation of all minor actinides are extremely impeded by the presence of curium, and the implementation constraints often exceed that of the scenarios, in which only americium is transmuted, by one order of magnitude. The economic studies conducted show that the cost increase related to the transmutation process could vary 5–9% in SFRs and 26% in the case of accelerator driven systems (ADSs).

Spanish participants implemented a study to analyse in terms of available resources, waste transmutation and economic implications the impact of the implementation of the four reference scenarios on a European nuclear fleet. The analysis performed has shown the feasibility of all considered scenarios in terms of fissile and fertile inventories [5.2]. Two scenarios were considered: in one, fast reactors were introduced to recycle and burn the plutonium only; in the other, minor actinides were subject to transmutation as achieved through either burning them in fast reactors that are part of electricity generation network or incinerating them in dedicated ADSs while not using fast reactors for this purpose. In the first case, fast reactors were shown to be potentially effective in reducing the amount of plutonium for final disposal down to 1% of the total. In the second case, both considered scenarios were shown to be effective in dealing with minor actinides, however, resulting in an electricity cost increase from 20% for fast reactors to 35% for specialized ADSs. This ‘price’ having been paid, the volume of final disposal facility would decrease four fold for the fast reactor scenario and five fold for the ADS scenario. The costs of the facility would also go down notably, however — the corresponding effect in the discounted cost of electricity would be relatively small, from 11% to 4%.

A study on EU scenarios with transmutation option for nuclear phase out and continued nuclear scenarios is a summary of the project projects RED-IMPACT, PATEROS and ARCAS completed EU Framework Programmes. The regional approach was adopted to implement the innovative fuel cycles associated with partitioning and transmutation in Europe addressing the impact of different strategies in various countries. Fast reactors and ADSs were considered for transuranic and minor actinide transmutation purposes. The ADS type was found to be mostly adapted to ‘minor actinides’, and not ‘transuranic’, and thus more fit in a regional scenario where different countries with different objectives share resources, facilities and spent fuel inventories in order to minimize wastes. The expected beneficial potential of partitioning and transmutation (reduction of the radiotoxicity in a repository to the level of the radiotoxicity of the initial ore after few hundred years, and the reduction of the heat load in the repository by more than one order of magnitude) would apply to the whole region. The study also examined the economic aspects of introduction of fast reactors/ADSs for the transmutation purpose. The increased costs of electricity produced by ADSs could be balanced by their limited share in the energy mix and the bigger share of lower cost kW·h produced by LWRs.

The case study on minor actinide transmutation in SFRs done by participants from China performed comparative assessment of two fast reactor options to burn minor actinides produced by pressurized water reactors, one related to transuranic fuelled SFR and another — to a dedicated SFR — burner. No ultimate winner was found — dedicated burner reactors are likely to have more safety related issues requiring further resolution, but they are more effective and could be deployed in relatively small numbers. The results suggest that cooperative development and ownership of such potentially more expensive burner reactors may be of benefit.

5.1.5. Synergistic systems with inclusion of a thorium cycle

The case study on scenario of transition to thorium/^{233}U fuel cycle implemented by participants from India examined the potential of fast reactors with metallic fuel to speed up the buildup of fissile inventory needed for such a transition. This study was bound to Indian scenarios aimed at efficient utilization of the limited uranium and abundant thorium national resources. It was confirmed in the study that fast reactors using metallic fuel can play a significant role in shortening the time period of transition to the deployment of thorium/^{233}U based reactors.

A short summary of the major findings of the IAEA publication on the role of thorium to supplement fuel cycles of future NESs is also included in the publication [5.3]. In this study, it was noted that reactors of many types, including LWRs, HWRs, fast reactors, high temperature reactors and molten salt breeder reactors, can use thorium/^{233}U fuel with varying efficiency. The introduction of thorium to once through fuel cycles of LWR and HWR decreases plutonium and minor actinide content in the spent nuclear fuel. However, the enrichment and fuel fabrication costs are likely to increase. Thermal spectrum thorium reactors in a closed nuclear fuel cycle can provide approximately the same enhancements to uranium economy, enrichment, and fuel manufacturing efforts as with use of uranium–plutonium MOX fuel. The study concludes that under some geographical and infrastructural conditions, the application of thorium may be considered as a complementary option for NESs with fast reactors in the uranium–plutonium fuel cycle [5.3].

5.1.6. Development and elaboration of instruments for collaborative scenario simulation

Development and improving of the instruments for simulation of collaborative scenarios with different kind of NESs was a topic addressed in the case studies from Japan and the Russian Federation. The study from Japan provided the heterogeneous world model analysis carried out with FAMILY-21 code applied to the advanced LWR MOX based global scenario with reprocessing and single recycle of plutonium from LWR used fuel. Impacts on key indicators were investigated in a comparison between the homogeneous and the heterogeneous world models. It was found that in the heterogeneous world model the advanced LWR MOX share, the required reprocessing capacity and the HLW volume reduction are about half of those observed in the homogeneous world model. Thus, use of the heterogeneous world model that considers synergy among groups of countries with different nuclear energy policies, instead of relying upon the homogeneous world model, is shown to provide a more realistic simulation result.

Homogeneous and heterogeneous world NESs with LWRs, fast reactors, small and medium sized reactors, and high temperature reactors were considered by the participants from the Russian Federation to understand the sustainability potential, including non-electrical applications, of a supercritical LWR WWER-S. The study showed that advanced WWER-S with conversion ratio of about 0.8 coupled with the break-even fast reactors (breeding ratio ~1) could meet the demands of a nuclear energy evolution scenario with 5000 GW(e) reached by 2100 in terms of natural uranium resources. For higher global growth rates, the breeding ratios of fast reactors would need to be increased.

The case study on sensitivity of key indicators to the shares of the GAINS NG1/NG2/NG3 country groups was a follow-up to the heterogeneous synergistic world model developed in the GAINS project. The goal of this study was to determine the impact of changes in the shares of groups of countries with different policies with regard to the fuel cycle back end. The NG1 group represents countries pursuing a closed nuclear fuel cycle, NG2 group represents countries running thermal reactors in a once through fuel cycle with the spent fuel being directly disposed or sent to NG1, NG3 represents newcomers who intend to operate thermal reactors and cooperate with NG1 and NG2 in the front end and back end of the nuclear fuel cycle. The study noted significant effects in saving natural uranium resources and reducing spent nuclear fuel amount in the options with more intensive cooperation between the groups of countries.

5.1.7. Synergistic collaboration towards improved economy

Comparative economic analysis of selected synergistic and non-synergistic scenarios examined the magnitude of possible effects in investment cost reduction through centralization of the fuel cycle back end facilities, owing to the economy of scale effects. An important insight is that, with discount factor being used, levelized unit energy cost (LUEC) alone is not an adequate indicator for comparative analysis of longer term sustainability options and needs to be amended by cash flow analysis. The latter has shown that the decrease of the investments in fuel cycle for the synergistic case may reach 14% in the short term, 52% in the medium term and 62% in the longer term, compared to a non-synergistic case. The corresponding savings in cash can then amount to tens of billions of US dollars.

5.1.8. Nuclear energy system evolution scenarios not considered in previous INPRO studies

Participants of the SYNERGIES project examined a few scenarios that have not been addressed by INPRO previously. Some of such scenarios compared synergistic and non-synergistic LWR/fast reactor based NESs. In contrast with the main focus of the SYNERGIES studies, one of the examined scenarios considered independent introduction of fast reactors with the enriched uranium based startup fuel load (with subsequent recycle of their own fissile self-sufficient fuel). Heavy liquid metal cooled reactors were considered for this purpose with very short time of external fuel cycle (~1 year), assuming on-site collocation of a closed fuel cycle facility. It was found that for the demand under consideration the uranium startup fuelled fleet of heavy liquid metal cooled fast reactors could by the end of the century exceed the fleet of the plutonium startup fuelled SFRs by a factor of 1.5. Savings of natural uranium in the uranium fuel loaded LWR/fast reactor NES in comparison with the LWR based NES are about 40%. Options with the uranium and plutonium startup fuelled fast reactors both offer comparable natural uranium savings by the year 2100. While introduction of the uranium startup fuelled fast reactors allows the rapid growth of their capacity, this option would lead to a strong competition with thermal reactors with respect to natural uranium and reprocessing capacities in the short and medium term. The essential disadvantage of the strategy with the startup of fast reactors on enriched uranium fuel with subsequent recycle of their own used fuel is that, on itself, it does not address the issue of the thermal reactors spent fuel accumulation, which is proportional to the energy produced by such reactors.

One of the studies performed by participants from Ukraine explored the possibility of broad deployment of nuclear reactors for non-electrical applications (heat production) and also assessed nuclear energy development scenarios based on the innovative (referred to as Generation IV) reactors. Scenarios of replacement of the fossil fuelled power units used for heat generation by small and medium sized reactors and broad deployment of the supercritical water reactors were considered. Both these options were found plausible for the country in scenarios with NESs based on a once through fuel cycle. With regard to the fuel cycle back end, it was found reasonable to extend the capacity of a centralized long term spent fuel storage facility, so as to optimize the economic expenditures and minimize the deployment of dry spent fuel storage facilities at each nuclear power plant.

5.2. DRIVERS AND IMPEDIMENTS FOR SYNERGISTIC COLLABORATION

5.2.1. Drivers

The SYNERGIES scenario analyses presented in Section 3 identify the competitive economy to be the primary driver for cooperation among countries. In this, technology user and, especially, newcomer countries look for the solutions with the minimum LUEC (sometimes also referred to as levelized cost of electricity).

The LUEC was found to be insufficient on its own when used for comparative analysis of possible sustainable NES options in the medium and long term. With differences in absolute costs of the future (say, in 40 or 50 years from now), NES options ranging from billions to tens of billions of US dollars, their impact on LUEC will be within just a few per cent, owing to the discount rate embedded in LUEC.

Different from technology users, some technology holder countries are running large and costly RD&D programmes on innovative nuclear reactors and fuel cycles. These developments are being driven by strategic and business growth motivations with the intention to become a source of nuclear technologies and services to huge anticipated national and world markets.[1] The economic studies performed [5.4] indicate that multibillion overall investments in innovative nuclear technology make economic sense only in the case when their final products are deployed at a large scale. Here, synergistic collaboration with technology user and newcomer countries could be helpful to take advantage of the economic benefits associated with the economy of scale of fuel cycle facilities and the economy of accelerated learning for nuclear power plants to reduce the costs for both, supplied nuclear power plants and provided fuel cycle services with benefits for all. Should such economies work, it could be a 'win-win' strategy for both, technology holders and technology users and newcomers.

In turn, the motivations of technology holder countries to pursue innovations in nuclear reactors and fuel cycles are inherently affected by the availability and cost of natural resources (e.g. uranium) and the situation with the progressive accumulation of spent nuclear fuel from thermal reactors operated in a once through fuel cycle. Should these problems aggravate, the motivations to pursue innovations will become stronger. At the moment, there are no sharp edges related to these, although progressive accumulation of spent fuel starts to press in places. With an increased role of these drivers for innovation, the motivation for both, technology holders and technology users is to facilitate the deployment of these innovative technologies and services.

Along with competitive economics, other potential drivers for synergistic cooperation in sustainable NES were identified by SYNERGIES participants, which could be related to the solution of some public acceptance or social issues, such as the control of plutonium inventories in storage to reduce proliferation and security concerns, minimization of the amount of HLW to simplify siting acceptable geological disposal solutions with minimum environmental impacts and footprints, considerations of increased energy independence (non-reliance on natural uranium with its potentially volatile price), and preservation of natural resources (e.g. natural uranium for countries with large targeted nuclear programmes), among other things.

The studies presented in Section 3 indicate that some of these drivers, or combinations thereof, may actually 'work' when the relevant disadvantages in economics are relatively small (a few per cent of the LUEC). However, the known current practice (the European Union's limited LWR spent fuel reprocessing and MOX fuel supply for a single recycle in LWRs) indicates such collaborations are limited in scale and undertaken by more wealthy and experienced users, including those who made a nuclear phase out decision. In the case of larger increases of global nuclear energy with the associated potential of resource insufficiencies, HLW accumulation and increased proliferation and security concerns, one could expect these public acceptance and social related drivers to work more effectively for synergistic collaboration targeted at nuclear energy sustainability.

5.2.2. Impediments

The identified impediments are related to the institutions and infrastructure to be associated with cooperation among countries. The fourth INPRO Dialogue Forum[2], as well as technical meetings of the SYNERGIES project have revealed a number of impediments on this way, including:

(a) National laws in some Member States prohibiting spent fuel transport across national borders.
(b) Non-available or insufficiently elaborated institutional procedures to govern nuclear fuel/HLW transactions and price formation mechanisms for such transactions.
(c) National laws that permit the return of ultimate waste (e.g. fission products and minor actinides) only of the same isotopic content as in the originally exported fuel. This would hamper the operations of a large fuel

[1] Investments in RD&D can be accounted for in the least cost energy models if they cover long time horizon and the benefits of such investments are materialized in terms of lower costs of construction and operation of nuclear power plants and fuel cycle facilities.

[2] See Appendix IV and www.iaea.org/INPRO/4th_Dialogue_Forum/index.html

cycle back end service provider or international fuel cycle centre for which it would be non-expedient to reprocess spent fuel individually for each customer.

(d) Regional directives narrowing the competition for reprocessing services and potentially many others.[3]

Timely overcoming the above mentioned impediments of institutional and infrastructure is a necessary step to enable synergistic collaboration among countries towards sustainable nuclear energy. Taking into account the time needed to change national laws and develop new institutional procedures may be a priority task for the near and medium term. The first step here would be to investigate the scope of legal and institutional issues in interested technology holder, technology user and newcomer countries more specifically and with higher degree of detail.

Finally, political and economic instability are identified as impediments that could hamper cooperation among countries.

5.2.3. Limitations

Case studies presented in Section 3 point to the multiple possible technical limitations for 'win-win' synergistic collaboration related to reasonable, affordable and timely availability of nuclear materials, advanced nuclear power plant technologies such as fast reactors and nuclear fuel cycle capacities.

In many scenarios presented in Section 3, there are situations where, for example, there might not be enough plutonium from reprocessed LWR fuel to produce initial fuel loads for fast reactors deployed at a particular rate. There could also be very high, but very short term, demands in reprocessing and fuel fabrication capacities — with lifetimes of these enterprises being 40 years or more. It would be difficult to find an investor for such an enterprise that would work at full capacity only for a few years. The observed imbalances are, among others, conditioned by spent fuel cooling, reprocessing and fuel fabrication times. Not all scenarios are possible and practicable. The potential presence of the impediments in Section 5.2.2 indicates that careful nuclear energy development scenario analysis is helpful in defining long term national nuclear energy strategies, as well as in assessing options of cooperation with other countries. To make the results of such analysis meaningful and practicable, careful collection and verification of the input data is needed.

The analysis of multiple cases has indicated that a systems view, across multiple Member States, covering the medium to longer term is essential to allow a proper assessment of synergistic potential. The systems view needs to include proper treatment of uncertainties and risks impacting decision making on sustainable NES synergies.

5.3. INSIGHTS ON THE SYNERGISTIC APPROACH AND ITS IMPLEMENTATION

Synergies among technological options related to nuclear power plant types and their fuel cycles (e.g. reprocessing or recycling of spent nuclear fuel as MOX, partitioning and transmutation) as well as collaboration policies of the technology suppliers and technology users and newcomer countries could be of benefit for speeding up transitioning to NESs of enhanced sustainability. However, collaborations would be viable only if based on a 'win-win' strategy for both suppliers and users ('by sharing, we win together'). In this, the 'not-invented-here syndrome' from some technology holder or aspiring technology holder countries can hamper collaboration. Synergistic collaborations in fuel cycle back end offer higher rates of capacity growth and larger capacity centralized fuel cycle enterprises which would help to exploit the economy of learning and the economy of scale curves and support 'win-win' collaborative strategies through the resulting economic benefits for all.

Implementation of national or collaborative scenarios of nuclear energy evolution can face multiple impediments related to material imbalance at certain points in time or timely unavailability/uneven use of back end fuel cycle capacities. The potential presence of the impediments in Section 5.2.2 indicates that careful nuclear energy development scenario analysis is helpful in defining long term national nuclear energy strategies, as well as in assessing options of cooperation with other countries. To make the results of such analysis meaningful and practicable, careful collection and verification of the input data is needed.

Synergistic collaborations among countries in fuel cycle back end may be prevented or hampered by the impediments of institutional and infrastructure nature. Finding pathways to overcome such impediments is a

[3] Public acceptance, safety and proliferation resistance concerns can also be mentioned in this context.

necessary step to enable cooperative countries' move towards sustainable nuclear energy. Taking into account time needed to change national laws and develop new institutional procedures such a resolution may be a priority task for the near and medium term. The first step here would be to investigate the scope of legal and institutional issues in interested technology holder, technology user and newcomer countries more specifically and with high degree of detail.

Participants of the INPRO Dialogue Forum on drivers and impediments for regional cooperation on the way to sustainable NESs, in Vienna in 2012, discussed synergistic approaches that would combine various NES options deployed within different countries into a global NES of enhanced sustainability.[4] All participants embraced the idea that such synergistic development would and could be beneficial, though the drivers towards such development should primarily be induced by the current nuclear technology leaders (e.g. China, France, India, Japan, Republic of Korea, Russian Federation and United States of America).

Synergistic collaborations among technology holders and technology users in fuel cycle back ends are likely to start from services being provided by fuel cycle service vendors to the technology users under individual contracts governed by bilateral agreements between countries (see Appendix V). In this, certain technology users might turn to have bilateral agreements with countries hosting certain vendors, and the fact that quite a number of vendors are likely to emerge in the near to medium term could secure a certain competition preventing the monopoly. However, at the Forum the representatives of newcomer countries indicated that an option of outsourcing of the back end fuel cycle services was viewed as preferable only in the short term. In the medium and long term, they see an international solution for fuel cycle back end as preferable, to exclude any monopolistic or cartel arrangement approaches.

5.4. NEAR AND MEDIUM TERM ACTIONS TOWARDS ENHANCED NUCLEAR ENERGY SUSTAINABILITY

The basic concept of SYNERGIES with respect to sustainability is to have the whole achieve more than the parts. If one partner in a synergistic collaboration is achieving enhanced sustainability, then the other partner could achieve the same enhancement without the requisite investment in technologies and the related infrastructure. International cooperation could help to expand the benefits of innovative technologies to those users who have no plans to deploy them domestically.

Near and medium term actions are needed to continue to ensure and improve the longer term sustainability of global nuclear energy. These actions can be grouped into several areas, including technology development, institutional developments, international cooperation and other. All of these areas can benefit from collaboration and the resulting synergies.

Many of the options for improving sustainability require development of advanced technologies or improvements in technologies that have seen only limited deployment. Near and medium term actions for technology development are focused on developing and demonstrating enabling technologies for the sustainability improvement options. The maturation of these technologies in the near and medium terms will help to enhance sustainability in the longer term, even if the technology holders only use them for domestic programmes. Use of these technologies in synergistic activities to assist other less developed programmes would further advance global sustainability. A key challenge for all advanced nuclear technologies is to improve economic performance.

Looking forward to manage growing SNF inventories in the near to medium term, geological repositories need to be opened for SNF disposal or reprocessing capacities need to be expanded and geological repositories opened for disposal of HLW. Either option will allow for reductions in SNF inventories while providing a waste solution missing from today's NES.

The successful opening and operation of one or more repositories is likely to reduce public uncertainties about nuclear waste and improve the associated social attitudes concerning specific repository projects, enabling more rapid deployment later, including potentially the deployment of regional repositories accepting waste from multiple countries. Depending on waste acceptance criteria, the startup of repositories may also influence decisions on direct disposal versus reprocessing of SNF.

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[4] See Appendix IV and www.iaea.org/INPRO/4th_Dialogue_Forum/index.html

In the medium term, initial deployment of fast spectrum reactors is anticipated. This initial deployment could serve many purposes. First, it will help to reduce the technical risk associated with industrial scale application of these technologies. Second, experience in the construction and operation of a limited number of fast reactors will provide important lessons prior to a more rapid expansion of reactors later. Third, the initial facilities will help answer questions about the true cost of fast reactors, reducing the economic uncertainties and enabling better analyses of the costs and benefits of transition to closed fuel cycles.

A number of institutional developments would help to encourage more synergies on NES that would lead to more effective management and operations of nuclear systems and potentially to higher utilization of nuclear fuel cycle facilities. These efficiencies would in turn result in improved economics of NES. Many are in the areas of cooperation on planning and personnel development that require limited investments. Others are related to nuclear facilities and management of materials and wastes.

Both newcomer countries and countries with existing nuclear development programmes can benefit from expertise and information sharing on licensing, regulations, radioprotection and environmental impact assessment, among other things. Sharing of human resources and expertise can extend beyond regulations and safety to include routine operations. While IAEA international safeguards can provide assurances to the world of the peaceful intent of nuclear energy users, regional groups such as the Brazilian–Argentine Agency for Accounting and Control of Nuclear Materials can also improve trust and foster cooperation.

There are historical and ongoing activities involving one party developing reprocessing capacity initially for domestic purposes and then selling reprocessing services to other parties, as well as those related to transboundary movement of spent fuel for storage or recycle in another country. These activities have resulted in the establishment of important institutional mechanisms to support the transfer of irradiated materials between countries, a key enabler for further expansion of cooperative synergistic activities. Such mechanisms need to be examined to ensure they will remain sufficient, assuming a substantial expansion in the international transfer of spent fuels, reconstituted fresh fuels and waste materials.

The current practice for management of spent nuclear fuel in most countries with NESs is interim storage pending development of geological repositories. One issue with interim storage is the lack of financial incentive to move on to a more permanent solution. Standard economic treatment of net present value and discounting consistently shows the cost of long term interim storage is minimal and the larger disposal investments cost less if postponed. Because disposal costs are incurred in the near term but the benefits are distributed over very long time horizons, the standard application of discounting reduces values far into the future to essentially zero in present day terms. However, such textbook application of economic theory fails to address the intergenerational aspect of sustainability. New economic models are needed in fuel cycle analyses to better model the costs of current practices and the benefits of sustainability.

Plans and projections are not guarantees that research will be successful or that development will occur on schedule. However, they do provide a vision of what is being attempted. When such visions are shared, groups can work together or independently to achieve those visions. Either approach increases the probability a vision will be realized. The large size and complicated nature of NESs require significant human and capital resources be applied in multiple areas simultaneously. Shared visions can help to coordinate these efforts by providing a roadmap for many (or for all) to follow. The more countries that are willing to share their plans and projections, the better the research, equipment, training and other providers can plan their own efforts. This can improve the overall efficiency of all parts of the global system.

In the near term, general roadmaps on the timing of nuclear reactor deployments can provide a starting point by indicating the level of construction services and fuel cycle services needed. Related workforce training, fuel cycle infrastructure development and other needs can then be developed. When these plans include newcomer countries, the related development on institutional mechanisms, such as regulatory agencies, can better be assisted. When the plans include assumptions about services such as fuel lease/take back, then potential service providers can better develop their own business plans, and improved institutional measures can be developed in advance of the need for their application. When these roadmaps include advanced reactors and advanced fuel cycles, they can also provide the basis for R&D roadmaps, which themselves can help to catalyse development of shared research facilities.

Many plans are already shared, but there has not been an effort to collect and integrate these plans into a global shared vision. Due to the cascading impact of a shared nuclear infrastructure development plan, a nuclear roadmapping effort could be recommended as one of the first near term activities.

REFERENCES TO SECTION 5

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[5.2] MERINO RODRÍGUEZ, I., ÁLVAREZ-VELARDE, F., MARTÍN-FUERTES, F., Analysis of advanced European nuclear fuel cycle scenarios including transmutation and economic estimates, Ann. Nucl. Energy 70 (2014) 240–247.

[5.3] INTERNATIONAL ATOMIC ENERGY AGENCY, Role of Thorium to Supplement Fuel Cycles of Future Nuclear Energy Systems, IAEA Nuclear Energy Series No. NF-T-2.4, IAEA, Vienna (2012).

[5.4] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability: Final Report of the INPRO Collaborative Project GAINS, IAEA Nuclear Energy Series No. NP-T-1.14, IAEA, Vienna (2013).

Appendix I

KEY INDICATORS FOR COLLABORATIVE NUCLEAR ENERGY SYSTEM SCENARIO EVALUATION WITH REGARD TO SUSTAINABILITY

One of the main objectives of the Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES) collaborative project is to evaluate the driving forces and impediments behind possible collaborative architectures and scenarios and to highlight those that could be driven continually by both users and suppliers' interests. To achieve this objective the project focused on identifying and analysing key indicators and evaluation parameters in synergistic collaboration. Key indicators have been reviewed and screened through the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) methodology reports, the Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS) collaborative project report, the fourth INPRO Dialogue Forum on Drivers and impediments for regional cooperation on the way to sustainable nuclear energy systems (NESs), held in Vienna in 2012, and by the participants to the SYNERGIES collaborative project.

INPRO methodology was designed as a tool for assessing the capabilities of a national NES to meet specified requirements for sustainability. INPRO methodology identifies seven assessment areas: economics, infrastructure, waste management, proliferation resistance, environment stressors, resource depletion and safety. For each of these assessment areas, the INPRO methodology identifies a hierarchical set of basic principles, user requirements and criteria (with indicators and acceptance limits) as the basis for the assessment. Through a bottom–up approach, the fulfillment of a criterion is confirmed by an indicator complying with the acceptance limit(s); the fulfillment of a user requirement is confirmed by the fulfillment of the corresponding criterion (criteria); and the fulfillment of a basic principle is achieved by meeting the related user requirement(s). To confirm NES sustainability using the INPRO methodology assessment, 14 basic principles, 52 user requirements and 125 criteria with indicators and acceptance limits need to be satisfied. INPRO methodology manuals provided a useful resource for the participants to the GAINS collaborative project.

The GAINS framework is aimed for comparing options and possible scenarios at the national, regional and global levels. Accordingly, the GAINS framework relates to INPRO methodology primarily through the concept of key indicators introduced in INPRO methodology reports. A key indicator should have a distinctive capability for capturing the essence of a given user requirement, basic principle or INPRO assessment area. It should provide a means to establish in a specific area targets to be reached via RD&D and to track progress towards the targets during the execution of the RD&D programme.

Key indicators may be formulated by selecting a specific indicator or user requirement used for screening and comparative evaluations, by grouping a few existing indicators or, in some cases, even by specifying a new indicator. For a given innovative NES, the key indicator is chosen taking into account relevant and salient design features, technological or institutional approaches, and boundary conditions, such as alternative sources of energy supply or industrial capability. An individual technology holder might identify key indicators of particular interest, or a group of technology holders might identify key indicators to be addressed through a collaborative project. A group of technology users/adopters may also wish to enter into a collaborative project (e.g. to develop a regional capacity in an area of infrastructure such as training) which could involve one or more technology holders. They too might be interested in identifying key indicators to track the progress of their collaboration.

Each key indicator should be distinct and should not overlap with any other, as it should be able to discriminate between different concepts of innovative NES. Key indicators can be chosen from among existing INPRO indicators with good discriminating capabilities. Minimization of the number of key indicators facilitates analysis based on implementation of a scenario based approach.

The GAINS framework provides 10 key indicators with associated evaluation parameters. The evaluation parameters can serve as subindicators which give an additional depth to the estimation of the NES sustainability. The set of key indicators and evaluation parameters provided is based on more than 100 indicators comprising all assessment areas of the INPRO methodology. These key indicators and evaluation parameters depict nuclear power production of a global NES according to reactor type, resources, discharged fuel, radioactive waste, fuel cycle services, costs and investments.

The fourth INPRO Dialogue Forum discussed issues related to sustainable nuclear energy development and deployment, and generated suggestions for amending the list of key indicators developed in GAINS collaborative project. Before and during the Forum, all participants were asked to suggest important areas where key indicators could be further defined to measure benefits achieved through regional collaboration in transition scenarios to future sustainable NESs. Potential benefits of cooperation are associated with minimizing infrastructure effort for national NESs of individual countries; suggesting sound solutions for spent nuclear fuel utilization and disposal; enabling optimum use of the available resources of all kinds; minimizing costs owing to the economy of scale and other factors; and ensuring that international commitments are met by all countries in a more easy and transparent way. However, the feasibility of any collaborative transition to sustainable NESs depends on the balance of the driving forces and impediments all the way through such a transition.

Analysis of responses given by the Member State questionnaires makes it possible to draw several conclusions:

(a) All respondents see cooperation among countries as a necessary condition for making a transition to future sustainable NESs.
(b) Cooperation on nuclear power plants has the highest priority in the near term (2012–2030) for both technology holder/user countries and newcomer countries, and is also rated as very important in the medium (2030–2050) and long (2050–2100) terms.
(c) Cooperation on final disposal of waste is the second near term priority, offering to the ‘newcomers’ a good chance to initiate future sustainable NESs from the outset of a national nuclear power programme.
(d) In the medium and long term, cooperation on final disposal of waste becomes the top priority for technology holder and user countries. The newcomers also rate it important, but believe that spent fuel storage would remain the best option and highest priority for cooperation in the long term.
(e) Respondents from newcomer countries prefer global and regional solutions for the back end of the fuel cycle in short, medium and long terms. Technology holder and user countries prefer national solutions in all terms.
(f) Technology holders and users prefer final disposal of spent nuclear fuel without reprocessing in the short and medium term. Newcomers are more optimistic on reprocessing (either in another country or in a global/regional nuclear fuel cycle centre). In their view, final disposal of only fission products is a preference in all terms. To take broader advantage of a nuclear energy programme, over time more and more countries would target indigenous development of the non-sensitive stages of the nuclear fuel cycle (front end), including mining and milling and to a smaller extent conversion and fuel pellet/fuel assembly manufacturing. The preference is to have two or three independent suppliers to ensure the security of supply.
(g) Participants’ responses and discussions during the fourth INPRO Dialogue Forum confirmed the validity of the key indicators and evaluation parameters defined in GAINS collaborative project for the purpose of comparative evaluation of benefits resulting from regional cooperation on the path towards sustainable NESs.

The SYNERGIES collaborative project is based on the key indicators concept applied in the GAINS collaborative project. The existing key indicators and evaluation parameters already developed by GAINS and the fourth INPRO Dialogue Forum were reviewed to address in greater details issues in certain areas of interest. At the beginning of the SYNERGIES collaborative project, participants screened existing INPRO and GAINS key indicators to assess their applicability for SYNERGIES studies and suggested new key indicators and suitable modifications to present ones. The participants assessed the relative importance of the proposed key indicators for different Member States. The first list of proposed indicators included 84 key indicators.

Participants, observers and task leaders ranked the 84 key indicators on a scale of 1 to 5 (5 signifies the most important). The average score is calculated from the sum of the ratings divided by the number of corresponding respondents. The results show that the highest score is 4.7 and the lowest is 3.0, with a response spread of 0 to 5 (one respondent provided a score of zero to show the absence of such plan in the country). In total, 34 out of the 84 key indicators received an average rating exceeding the score of 4.1. Table I.1 presents rankings for key indicators receiving the highest scores of 4.1 or greater, along with range of responses as a whole (84 key indicators). It was suggested to differentiate between the calculable primary key indicators that focus on sustainability and key indicators that serve as a measurement of collaboration. For instance, the key indicator on natural uranium resources refers to sustainability, while the key indicator on economics serves as a driver towards collaboration. Since SYNERGIES emphasizes ‘win-win’ situations, the benefits of collaboration should be discussed to address issues such as whether the party gaining more profits should share with the party that experiences losses.

TABLE I.1. RESULTS OF RANKING OF KEY INDICATORS EXCEEDING THE SCORE OF 4.1

Key indicators	Av. score	Range
1. Macroeconomic indicators	4.7	4–5
2. Cumulative natural uranium consumption*	4.7	3–5
3. Long term spent fuel storage*	4.7	3–5
4. Legal framework	4.6	2–5
5. Plutonium and minor actinides in long term storage*	4.6	3–5
6. Long term commitment	4.5	3–5
7. Availability of resources	4.5	4–5
8. $Q_j(t)$ = quantity of material available	4.5	4–5
9. Energy delivered per tonne of uranium mined	4.5	4–5
10. Energy security	4.5	4–5
11. Security of supply	4.5	3–5
12. Government policy	4.4	3–5
13. Financial resources	4.4	3–5
14. Net minor actinides burned (or radio toxicity decreased) per unit net energy generated	4.4	4–5
15. IN4.1: Availability of human resources	4.3	2–5
16. State's obligations and commitments	4.3	3–5
17. IN4.2.1: RD&D defined and performed	4.3	3–5
18. Public health and environmental issues	4.3	3–5
19. Annual quantities of spent fuel preprocessing required	4.3	3–5
20. Cost of hydrogen generation and transportation to end user, per unit energy usable	4.3	3–5
21. Public acceptance	4.2	3–5
22. Availability of technology	4.2	3–5
23. Scaling understood	4.2	3–5
24. Energy independence	4.2	1–5
25. Human resources	4.2	3–5
26. Technical indicators	4.1	3–5
27. Energy delivered per tonne of thorium mined	4.1	1–5
28. Power production*	4.1	3–5
29. Cost and investment*	4.1	3–5
30. Legal and institutional and other considerations	4.1	3–5
31. Nuclear material resources (fissile and fertile) accounting	4.1	3–5
32. Suggestion: modified minor actinides related key indicator from GAINS	4.1	3–5
33. Probability of toxic release from hydrogen plant, established by a probabilistic safety analysis	4.1	3–5
34. Wastes produced (non-nuclear, toxic and non-toxic) per unit energy generated	4.1	3–5

* Key indicators used in GAINS and SYNERGIES.

The experience showed that the first list of indicators is broader than the list of indicators actually calculated. The final list of key indicators and evaluation parameters actually used in SYNERGIES studies are compiled in Table I.2. As in the case of the GAINS collaborative project, areas of interest include power production, nuclear material resources, discharged fuel, radioactive waste and minor actinides, fuel cycle services and costs and investment.

Key indicators have been defined for selected INPRO assessment areas that reflect the focus areas of the SYNERGIES collaborative project: economics (E), environment resources (ER), environment stressors (ES), proliferation resistance (PR), infrastructure (I) and waste management (WM). Regarding the key indicators used in GAINS collaborative project, participants of the SYNERGIES collaborative project have decided to remove the key indicators for further consideration.

SYNERGIES studies include not only global or regional levels but also the national level. For this type of scenario, the set of GAINS key indicators and evaluation parameters developed for global architectures were adapted to a more localized application of the framework. The studies generated four groups of key indicators:

— Key indicators already addressed in full by GAINS collaborative project;
— Key indicators modified from those of GAINS collaborative project;
— Key indicators introduced, but not yet implemented in GAINS collaborative project;
— New key indicators relatively to GAINS collaborative project.

Some studies expanded the GAINS framework and included additional key indicators and evaluation parameters of interest. For example, some studies measured uranium consumption with the help of different key indicators which were appropriate for particular studies and evaluation parameters, such as annual/cumulative natural uranium requirements (as fully addressed in the gains framework) and modified evaluation parameters for natural uranium savings derived from (a) reprocessed uranium use and (b) mixed oxide use, which take into account the time of exhaustion of conventional natural uranium resources.

The GAINS database does not include inputs for calculating some of the key indicators or evaluation parameters. Therefore, economic indicators such as the levelized unit energy cost (LUEC) and investments were identified but not used in GAINS studies. Economic data for NESs were collected within the SYNERGIES collaborative project for a more complete application of the GAINS framework in the area of economics. The data are sufficient to calculate LUEC for comparative economic analysis of the various NES options. Data are presented in tables and graphics, and in each case appear as a range with minimum, maximum and recommended values. Economies of scale curves for fuel enrichment and reprocessing facilities are also included.

Based on updated key indicators, SYNERGIES studies measure the benefits of drivers and impediments to collaboration among countries in transition to a globally sustainable NES and identify the transition scenarios which offer a ‘win-win’ strategy for both technology holders and users. The key indicators quantify the degree to which the selected targets (e.g. minimized waste, minimized amounts of direct use materials in storage or minimized natural resource depletion) are approached in particular evolution scenarios. Key indicators are compared to determine the more promising options for achieving the selected targets. Possible benefits and issues between the different options also can be analysed.

TABLE I.2. KEY INDICATORS USED IN SYNERGIES STUDIES (ANNEXES I–XXVII)

Key indicators	Evaluation parameters	Units	Relevance to INPRO areas*	Relevance to GAINS
Power production				
1.1. Per annum electric/thermal energy generation growth by reactor type	1.1.1. Per annum electric energy generation growth by reactor type	GW·year	I	Fully addressed
	1.1.2. Per annum thermal energy generation growth by reactor type	GW·year	I	Modified
	1.1.3. Non-electrical production (a) hydrogen, (b) desalination, (c) heat	GW·year	I	New
	1.1.4. Commissioning and decommissioning rates	GW(e)/year	I, WM	Fully addressed
	1.1.5. Installed capacity	GW(e)	I, WM	Modified
Nuclear material resources				
2.1. Uranium consumption	2.1.1. Natural uranium requirements (a) annual, (b) cumulative	kt HM	ER, WM	Fully addressed
	2.1.2. Depleted uranium	kt HM	ES, ER	Fully addressed
	2.1.3. Reprocessed uranium	kt HM	ES, ER	Fully addressed
	2.1.4. Natural uranium saving from (a) reprocessed uranium use, (b) mixed oxide use, (c) DUPIC	kt HM	ER, PR, WM	Modified
	2.1.5. Time of exhaustion of conventional natural uranium resource	years	ER, PR, WM	Modified
	2.1.6. Natural uranium exhaustion	t HM	ER, PR, WM	Modified
2.2. Plutonium resources	2.2.1. (a) Plutonium in the system, (b) reprocessed plutonium, (c) reprocessed plutonium use, (d) reprocessed plutonium stock	t HM	ER, PR, WM	Fully addressed
	2.2.2. Plutonium saving	%	ER, PR, WM	New
2.3. Thorium consumption	2.3.1. Thorium	t HM	ER, WM	New
Discharged fuel				
3.1. Discharged fuel inventories	3.1.1. Discharged fuel inventories (a) annual spent generation, (b) long term spent fuel storage	kt HM+FP	WM, I	Fully addressed
Radioactive waste and minor actinides				

TABLE I.2. KEY INDICATORS USED IN SYNERGIES STUDIES (ANNEXES I–XXVII) (cont.)

Key indicators	Evaluation parameters	Units	Relevance to INPRO areas*	Relevance to GAINS
4.1. Minor actinides	4.1.1. MA inventories (a) reprocessed MA, (b) used MA, (c) MA stock, (e) MA in long term storage	t HM	ER, WM	Fully addressed
4.2. Plutonium	4.2.1. Plutonium in long term storage	t HM	ER, PR, WM	Fully addressed
4.3. Fission products	4.3.1. Reprocessed fission products	t	WM, I	Modified
4.4. Radiotoxicity and decay heat	4.4.1. Radiotoxicity and decay heat	kW, Sv/kW·h		Identified but not used
4.5. Low level waste disposal	4.5.1. Low level waste disposal (a) volume, (b) area	m^3, km^2	WM, I	New
4.6. High level waste disposal	4.6.1. High level waste disposal (a) volume, (b) area	m^3, km^2	WM, I	New
Fuel cycle services				
5.1. Nuclear fuel cycle infrastructure	5.1. Requirements to nuclear fuel cycle infrastructure, i.e. requirements, installed and new capacities for uranium, (a) mining, (b) conversion, (c) enrichment, (d) fuel fabrication, (e) reprocessing of spent fuel, spent nuclear fuel temporary storages and final repositories	SWU, t HM	PR, I	Modified
5.2. Annual quantities of fuel and waste material transported between groups	5.2.1. Annual quantities of fuel and waste material transported between groups	t HM	WM, PR, I	Fully addressed
5.3. Transmutation	5.3.1. Transmutation rate/capacity	kg/TW·h	WM, PR, I	New
System safety				
6.1. Annual collective risk per unit energy generation	6.1.1. Annual collective risk per unit energy generation	Risk/MW·h, or qualitative discussion	S	Identified but not used
Costs and investment				
7.1. Levelized unit energy cost	7.1.1. Levelized unit energy cost	US $/MW·h, €/kW·h,	E	Identified but not used
	7.1.2. Levelized fuel cycle unit of electricity cost	US $/MW·h,	E	Identified but not used
7.2. Investment	7.2.1. Annual and total investment (expenditure) in nuclear power plants	US $billion, or relative value	E	Identified but not used

TABLE I.2. KEY INDICATORS USED IN SYNERGIES STUDIES (ANNEXES I–XXVII) (cont.)

Key indicators	Evaluation parameters	Units	Relevance to INPRO areas*	Relevance to GAINS
	7.2.2. Annual and total investment (expenditure) in nuclear fuel cycles	US $billion; or relative value	E	Identified but not used
	7.2.2. Annual and total discounted investment in nuclear fuel cycles	US $billion; or relative value	E	Identified but not used
7.3. Uranium cost	7.3.1. Natural uranium cost perspective	US $/kg (t)	E	New
	7.3.2. Economic value of reprocessed uranium	US $/kg	E	New
7.4. Fuel cycle cost	7.4.1. Fuel cycle service cost (a) conversion, (b) enrichment, (c) fuel fabrication, (d) reprocessing	US $/kg SWU, US $/kg HM, US $/t SWU, US $/t HM	E	New
	7.4.2. Cumulative cost (a) enrichment, (b) reprocessing	US $	E	New
	7.4.3. Spent fuel/high level waste storage cost (a) interim, (b) final	US $, €	E	New
	7.4.4. Transmutation overcost	%	E	New

* Areas include: economics (E), environment resources (ER), environment stressors (ES), proliferation resistance (PR), infrastructure (I) and waste management (WM).

Note: DUPIC — direct use of spent pressurized water reactor fuel in CANDU reactors; FP — fission products; GAINS — Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle; HM — heavy metal; INPRO — International Project on Innovative Nuclear Reactors and Fuel Cycles; MA — minor actinides; SWU — separative work unit.

Appendix II

ECONOMIC ASSESSMENT DATA, METHODS AND TOOLS

The Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES) project considers economics as an important component in the assessment of transition scenarios and various collaborative architectures. International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) methodology for the area of economics provides a method and tool (Nuclear Economics Support Tool, NEST) to estimate a set of economic indicators based on electricity generating costs of existing and advanced reactors and associated fuel cycles including fast reactors and closed fuel cycle, investments in nuclear energy systems (NESs), and other figures of merit. These traditional economic indicators can be used if relevant unit costs are known (with reasonable uncertainties). To assess transition scenarios of dynamic NESs, the SYNERGIES project follows recommendations from the Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS) project and INPRO methodology to use two key indicators in the area of economics: electricity generation cost or levelized unit energy cost (LUEC); and total investments.

The estimation of economic indicators requires a set of economic and technical input data. The SYNERGIES collaborative project employs data collected for the following facilities: mining, milling, conversion, enrichment, fuel fabrication, long term storage, disposal of spent fuel, reprocessing, reprocessed products storage with their technical and economic data including capital costs, capacities, load factors and lifetimes.

II.1. INPUT DATA ON REACTORS AND FUEL CYCLE FACILITIES FOR ECONOMIC ANALYSIS

Collection and compilation of consistent and reliable input data on reactors and fuel cycle facilities is a significant challenge for economic analysis, as data sources have great uncertainty due to variation in specific national conditions and author assumptions. Furthermore, some investment data on existing technologies are unavailable due to commercial restrictions, and economic data on innovative technologies are either insufficiently reliable or unavailable due the absence of commercial experience.

The main objective of the SYNERGIES study is to show the relative impacts of various factors on the NES architectures, and particularly to evaluate the relative difference between synergistic and separate (non-synergistic) cases. As there is no intention to perform an accurate absolute cost calculation, the data used might not reflect actual industrial values. For the comparative economic analysis, it is important to use a consistent set of economic data with proper proportion of fuel costs rather than absolute values. If these costs proportionally increase or decrease, the percentage difference in cases costs will be the same.

The economic data used for reactors and fuel cycles were drawn from published literature [II.1–II.23]. It is fully recognized that the data are subject to change in the future and should be updated when new information is available.

II.1.1. Reactor cost data

One of the most comprehensive source of costs for reactor investment, operation and maintenance (O&M) is a joint report by the International Energy Agency and the OECD Nuclear Energy Agency, Projected Costs of Generating Electricity [II.1]. Data for the overnight, O&M costs of nuclear power plants by country extracted from the report are given in Figs II.1 and II.2.

The overnight cost comprises pre-construction, construction and contingency costs during construction, but not interest. Overnight costs vary from US $1700/kW(e) in China to US $5900/kW(e) in Switzerland and the Czech Republic. O&M costs, included fixed and variable costs, are in the range of US $7–30/MW·h. The overnight and O&M costs differ due to the national conditions, the lack of recent construction experience in some countries and country specific cost allocation schedules.

Figure II.3 shows fuel cycle costs including front end costs and back end costs associated with waste management. For most countries, fuel cycle costs range between US $8/MW·h and US $10/MW·h. The stacked bar graph in Fig. II.4 shows the total LUEC as well as its main components at 5% and 10% discount rates, respectively.

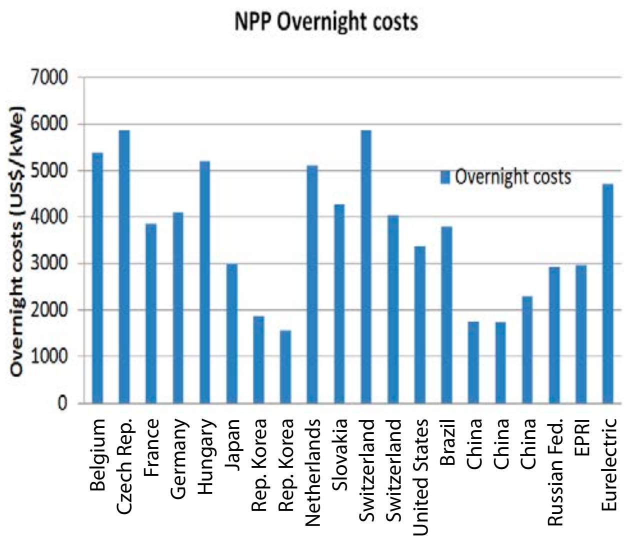


FIG. II.1. Nuclear power plant overnight costs.

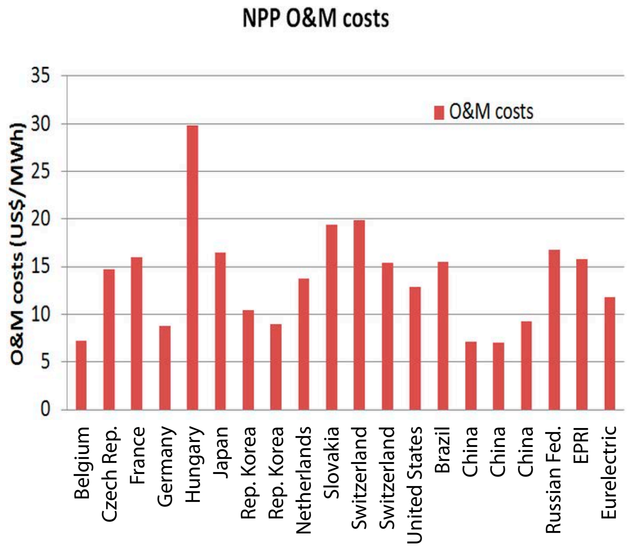


FIG. II.2. Nuclear power plant operation and maintenance costs.

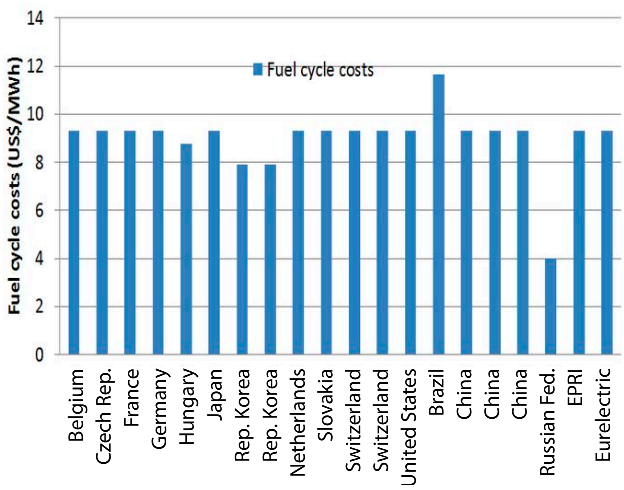


FIG. II.3. Fuel cycle costs.

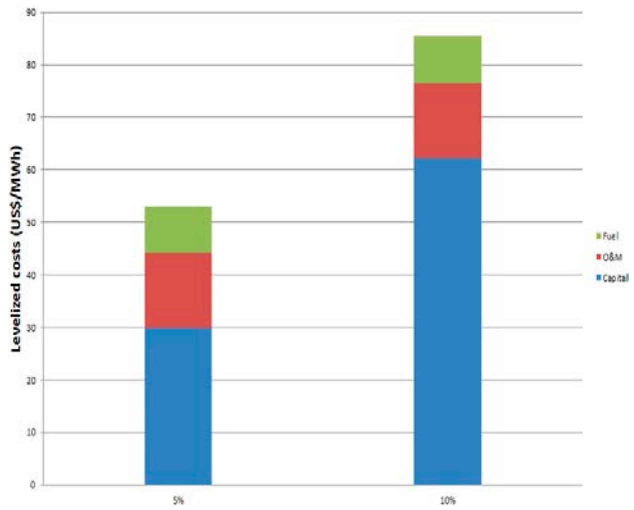


FIG. II.4. Levelized cost structure.

The cost components in LUEC bars comprise investment costs, O&M costs and fuel costs. The discount rate has a significant impact on capital costs, while O&M and fuel costs do not change with the discount rate. At a 5% discount rate, investment costs represent the largest portion of total levelized costs (57%), while O&M costs represent 27% and fuel cycle costs are around 16%. At a 10% discount rate, the percentage of investment in total levelized generation cost is around 73%; the other cost elements, O&M costs and fuel cycle costs, represent 17% and 10%, respectively. These figures include costs for refurbishment, waste treatment and decommissioning after a 60 year lifetime. Table II.1 summarizes data on overnight and O&M costs for light water reactor (LWR), heavy water reactor (HWR) and fast breeder reactor (FBR) based on data sources [II.1–II.4].

The uncertainty on fast reactor investment cost is a key issue for the eventual deployment of fast reactor based NESs. In the studies of Refs [II.14, II.19], a conservative approach was adopted, assuming that the upper bound for fast reactor capital costs would be 20% higher than investment costs of current generation pressurized water reactors (PWRs), while the lower bound would be the same target nominal value as PWRs. Other studies suggest that fast reactor capital costs could be even lower than PWR costs once the learning and series effect have occurred. Schemes involving fast reactors would become economically attractive if and when such investment cost reductions are achieved.

TABLE II.1. REACTOR COSTS

Item	Unit	Reactor type	Range	Reference value base year 2008
Overnight cost	US $/kW(e)	LWR	1500–6000 [II.1], base year 2010 1200–1900 [II.2], base year 2000 1800–3500 [II.4], base year 2008 4500 [II.20], base year 2010	3000
		HWR	1200–1900 [II.2], base year 2000	Same as PWR
		FBR (MOX)	1200–2300 [II.2], base year 2000 1800–5000 [II.4], base year 2008 20% higher than PWR	Upper boundary 20% higher than PWR Low boundary same as PWR
Fixed O&M cost	US $/kW/year	LWR	55–75	60
		HWR	55–75	60
		FBR (MOX)	55–80	60
Variable O&M cost	US $/MW·h	LWR	0.5–1	0.5
		HWR	0.5–1	0.5
		FBR (MOX)	0.5–2	0.5

Note: FBR — fast breeder reactor; HWR — heavy water reactor; LWR — light water reactor; MOX — mixed oxide; PWR — pressurized water reactor.

II.1.2. Fuel cycle costs

The fuel cycle scheme considered in this study is based on uranium extraction, uranium conversion, enrichment, fuel fabrication (uranium oxide, UOX; mixed oxide, MOX), store of spent fuel, reprocessing (UOX and MOX), and final disposal of spent fuel and high level waste (HLW) as given in Table II.2. As mentioned earlier, the comparative economic analysis requires a consistent set of economic data with the proper proportion of fuel costs, rather than accurate absolute values. Table II.2 shows sets of all these data from different sources [II.2–II.5, II.7]. The data range includes low–normal–upper values of fuel step cost, and may vary from source to source. However, the sources provide information about the proportion of fuel cycle cost, as this is important for case comparison.

The term ‘service costs’ is introduced to distinguish these costs from the actual levelized fuel cycle cost. Service costs can be representative of the selling price of nuclear fuel services to the customer, including additional component (surplus value). Therefore, the price reflects more than the levelized cost. For example, the INPRO manual on economics [II.24] assumes the selling price of electricity is 30% higher than the cheapest alternative levelized discount cost for new plants.

Additional data from existing studies on waste disposal costs (including spent nuclear fuel and reprocessing of HLW) are compiled in Table II.3. The cost of HLW is represented in terms of the amount of original spent nuclear fuel in US $/kg HM.

Bunn [II.12] determines that disposal of reprocessing wastes leads to a cost savings of US $100–300/kg HM — from 25% to 75% of the currently estimated total cost of disposal of spent fuel. This study used the same range for disposal of reprocessing waste from fast reactor fuel as for reprocessing of LWR fuel. As reprocessing wastes from higher burnup fast reactor fuel have higher activity and higher volume (increasing the costs of disposal factor), the cost of disposal for wastes from reprocessing of the blanket fuel (which will have low burnup) and of the core fuel (which will have high burnup) are expected to be lower. The Boston Consulting Group [II.18] baseline assumption considers the unit cost for disposing of used MOX equivalent to the estimation of long term cost of disposing regular (LWR) used fuel. Advanced Fuel Cycle Cost Basis [II.4, II.5] provides the nominal cost for spent nuclear fuel disposition as US $650/kg HM, or US $16 250/kg FP based on an average fission product composition of 4% of initial heavy metal. The waste loading of the HLW is estimated to be improved by a factor of 2–10×, with

TABLE II.2. FUEL CYCLE SERVICE UNIT COSTS

Fuel cycle step	Unit	AFCCB [II.5] 2009	Th FC [II.3] 2012	OECD NEA [II.2] 2006	UxC [II.7] 2013
Base year of monetary unit		2008	2009	2000	2013
Uranium	US $/kg U	25–60–240	40–450	20–30–80	130 ($55/lb U)
Conversion	US $/kg U	5–10–15	3–8–12	3–5–8	11
Enrichment	US $/kg SWU	80–105–130	80–110–164	80–100–120	120
Fuel LWR UOX	US $/kg HM	200–240–300	200–275–300	200–250–300	
Fuel HWR UOX	US $/kg HM		65–85–135		
Fuel LWR MOX	US $/kg HM	1000–1950–4000 3000–3200–5000	1000–325–1500	1000–1250–1500	
Fuel FR MOX	US $/kg HM	1000–1950–4000	650–350–2500	1000–1500–2000	
Fuel FR Bl	US $/kg HM		350–350–700		
Repro LWR UOX	US $/kg HM	500–1000–1500 1100–2500	700–800–900	700–800–900	
Repro LWR MOX	US $/kg HM		700–800–1000	700–800–1000	
Repro FR MOX	US $/kg HM	700–1320–2080	1000–2000–2500	1000–2000–2500	
Repro FBR Bl	US $/kg HM		900–800–2500		
Pu storage	US $/kg Pu	3500–5000–6500	2000		
SNF storage LWR	US $/kg HM	100–120–300	Per year 5	100–150–200 Per year 5	
SNF storage FBR	US $/kg HM		Per year 7	200–300–500 Per year 5–7.5–20	
LWR SNF direct disposal	US $/kg HM	400–1000–1600	600		
HWR SNF direct disposal	US $/kg HM		73		

Note: Bl — blanket; F(B)R — fast (breeder) reactor; HM — heavy metal; HWR — heavy water reactor; LWR — light water reactor; MOX — mixed oxide; PWR — pressurized water reactor; SNF — spent nuclear fuel; SWU — separative work unit; UOX — uranium oxide.

TABLE II.3. WASTE DISPOSAL COST

Waste disposal	Unit	AFCCB [II.5] 2009	Th FC [II.3] 2012	MIT [II.16] 2011	Bunn [II.12] 2003	BCG [II.18] 2006
Base year of monetary unit		2008	2009	2007	2003	2005
LWR UOX SNF direct disposal	US $/kg HM	400–650–1000	600	470	400	600–700–1000
HWR SNF direct disposal	US $/kg HM		73			
Disposal of HLW from UOX	US $/kg HM			190	100–200–300	
	US $/kg FP	1625–500–8125		3650		
Disposal of HLW from FR	US $/kg HM			280		

Note: FR — fast reactor; HM — heavy metal; HWR — heavy water reactor; LWR — light water reactor; SNF — spent nuclear fuel; UOX — uranium oxide.

TABLE II.4. REPOSITORY COSTS [II.19]

Repository capacity (t HM)	Capital investment (US $bn, 2010)	Total specific cost (US $/kg HM, dr = 0%)
20 000	1.44–3.61–9.93	203–464–1152
40 000	2.17–5.42–14.89	153–313–743
120 000	151–208–341	119–213–470

a nominal loading of 2.5×. Therefore, the related HLW disposition costs are estimated to be US $1625–8125/kg FP, with a nominal cost of US $6500/kg FP.

The examples in Table II.4 illustrate the specific overnight investment costs for three different capacities of repositories: 20 000, 40 000 and 120 000 t HM [II.19]. To date, there have been no civilian geological repositories in operation, therefore cost estimates have a large degree of uncertainty and should be verified as facilities are constructed.

The specific costs (per kg HM) of an integrated reprocessing facility (including a reprocessing plant using aqueous technology, MOX fuel fabrication, and fission product/minor actinide vitrification plant) are illustrated in Table II.5 for different plant capacities and taking into account different discount rates [II.19]. Economies of scale and plant capacity as well as discount rate affect significantly on the economics of reprocessing. Other important factors include learning curve and optimization. Lower unit reprocessing costs can be obtained for facilities operating whole lifetime on maximum throughput.

The uranium resources for this study data were taken from the Red Book [II.13] and are divided into seven grades (a, b, c, d, e, f, g) according to their cost. Grades a–e refer to identified and undiscovered resources of various costs that comprise 17.5 million t of natural uranium (as shown in Table II.6). Grade f is associated with uranium in phosphates and has a deposit of 21 600 kt of uranium (recovery cost > US $350/kg U). Natural uranium resources are limited by 39 million t for the sum of all those grades. Resource of grade g is associated with uranium in sea water. It is assumed that the resource of grade e is practically unlimited (recovery > US $450/kg U).

TABLE II.5. SPECIFIC COST OF REPROCESSING [II.19]

Reprocessing plant capacity (t HM/year)	Total specific cost (US $/kg HM)		
	dr = 0%	dr = 3%	dr = 7%
800	933–1159–1384	1170–1474–1779	1687–2163–2640
1600	467–579–692	585–737–889	843–1082–1320

TABLE II.6. NATURAL URANIUM COSTS [II.13]

Recovery (US $/kg U)	Identified resources (t U)		Undiscovered resources (t U)		Phosphates (t U)
	Reasonably assured resources	Inferred resources	Prognosticated resources	Speculative resources	
< 40 (a)	493 900	187 000			
40–80 (b)	1 520 900	876 700	1 624 100		
80–130 (c)	1 440 700	808 000	1 073 900	3 543 800	21 600 000 (f)
130–260 (d)	923 200	846 200	143 300	318 300	
Cost range unassigned (e)				3 733 200	
	7 096 600		10 436 600		
Total	17 533 200				
	39 133 200				

Additional information on uranium cost can be found in Ref. [II.23]. This source complements Refs [II.21, II.22] by identifying where expanded and new uranium resources among 116 countries worldwide are projected to meet future demand through 2030. The study analyses recent and prospective spot and long term contract market activity, supply and demand trends, supplier developments and the outlook for prices over the short and long term. Cost curves for operational, planned, and potential projects were developed in this publication to identify those projects most likely to produce in the future, as well as expected cost curves for 2013, 2015 and 2020 production.

Reference [II.23] reports that in 2015 approximately 470 million t of primary product should be available to the market based on the current production plans. Only around 210 million t of U_3O_8, or 44% of projected global production in 2015, is expected to be available under the current spot price of US $90/kg U. At a cost of around US $130/kg U or above, a total of about 95 million t U is expected to be available, or 21% of projected production. Production in this higher cost range increases by 7% compared to the 2013 production cost curve, indicating the migration towards bringing on line higher cost projects as demand slowly increases. In 2020, only around 57 million t U, or 10% of projected global production in 2020, is expected to be available under the current spot price of US $90/kg U. At a cost of around US $130/kg U or above, a total of 290 million t U is expected to be available, or 49% of projected production. This is a sharp increase in production in the US $130/kg U or higher category, compared to just 21% in 2015. This shows that production costs increase significantly by 2020 with a number of higher cost projects expected to come on line in the 2015–2020 period.

Most sources include only the total fuel cycle cost or services costs, but this analysis considers capital investments in new fuel cycle facilities as well. Furthermore, economies of scale are taken into consideration, since scale factor may have a significant impact on per kilogram costs, depending on the size of new plants. Investment analysis and case comparison requires data on overnight cost of main fuel cycle facilities and its dependence versus installed capacity.

Reference [II.6] contains capacity, investment, overnight cost and O&M cost for different enrichment facilities. Levelized investment cost and total levelized cost from the source were recalculated considering a 5% discount rate. The calculation of LUEC assumes that the lifetime of a fuel cycle facility is 30 years, construction time is 3 years, and the capacity factor equals 1. Data are divided into three groups: future centrifuge facilities, operating centrifuge facilities (Europe and Japan), and existing centrifuge facilities (Russian Federation). Figures II.5 and II.6 arrange the overnight and levelized costs versus installed capacity. To calculate the levelized product cost (minimum price) of the production unit (covering all levelized costs of installing and operating a nuclear facility) the following data are needed as input:

— Overnight capital cost to construct the facility;
— O&M cost covering personnel, cost for input materials (such as UF_6), waste management cost and provision for decommissioning;
— Time distribution of each payment (capital and O&M) needed to install and run the facility;
— Discount rate.

Levelized product cost is presented only for future centrifuge facilities. The relationship between average costs and the reciprocal of size is estimated as the power trend line option proportional to the power of throughput. The scaling factor p is reported in Refs [II.5, II.12] in the range of approximately 0.6. Both curves for overnight cost and LUEC scale roughly with the p = 0.7 power of throughput. Thus, the cost of two plants (Cost1, Cost2) of different capacities (Capacity1, Capacity2) can be written as Cost1 = Cost2×(Capacity1/Capacity2)^p.

The reprocessing cost estimates are based on the limited statements that are available from studies from other sources [II.4, II.5]. The global market for commercial reprocessing has been shared by three reprocessing facilities: AREVA's La Hague site, in France; Sellafield, in the United Kingdom; and the Atomenergoprom's Mayak site, in the Russian Federation. References [II.4, II.5] provide capital cost and throughput estimates for various reprocessing plants design studies and actual facilities. The overnight cost and LUEC cost were calculated assuming that the lifetime of the fuel cycle facility is 40 years, the construction time is 5 years, and the capacity factor equals 1. Figures II.7 and II.8 arrange those data versus installed capacity with a scaling factor in the range of around 0.6.

Economies of scale may have a significant impact on specific costs, depending on the size of new plants. The most economical would be a plant size of 3000 t HM/year. Like reprocessing, fabricating plutonium into uranium–plutonium MOX fuel is expensive: large, capital intensive facilities are needed for safety reasons, and there are significant safeguards and security requirements for handling weapons usable material such as separated plutonium. While the data on capital costs for other fuel cycle facilities is not yet reliable and validated, some data gathered is presented in Table II.7 [II.8–II.12].

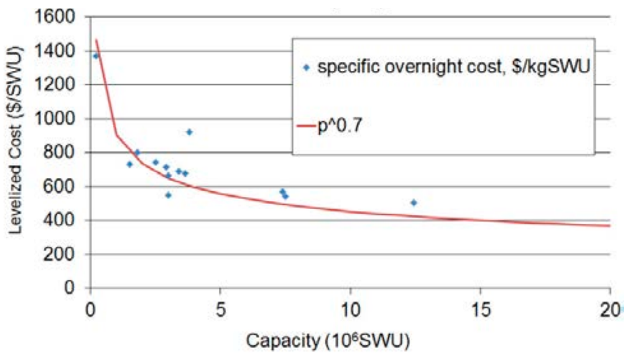


FIG. II.5. Overnight enrichment cost (US $2008/kg SWU) versus installed capacity.

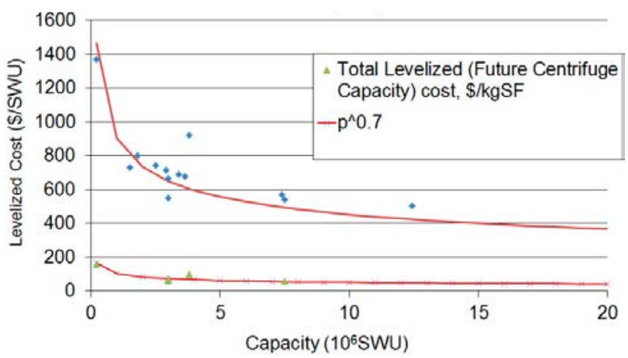


FIG. II.6. Levelized enrichment cost (US $2008/kg SWU) versus installed capacity.

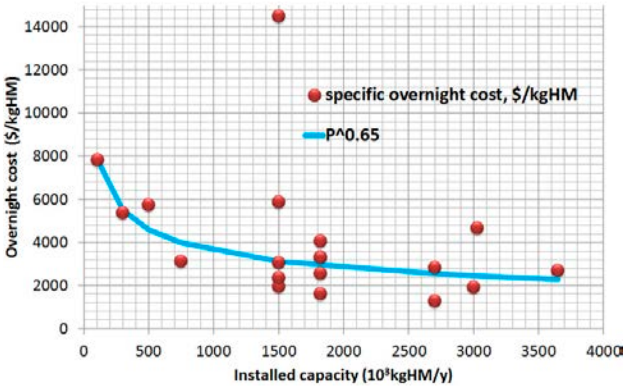


FIG. II.7. Overnight reprocessing cost (US $2008/kg HM) versus installed capacity.

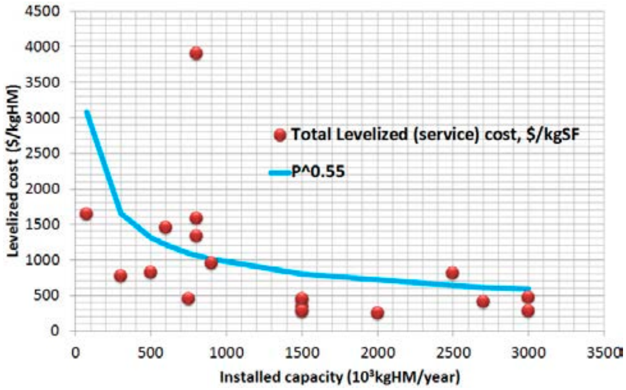


FIG. II.8. Levelized reprocessing cost (US $2008/kg HM) versus installed capacity.

TABLE II.7. FUEL CYCLE FACILITIES OVERNIGHT COSTS [II.8–II.12]

Fuel cycle facility	Unit	Univ. Chicago 2004 [II.8]	Harvard Univ. 2001 [II.9]	IAEA 2009 [II.10]	IAEA 1998 [II.11]	Bunn 2003 [II.12]
Mining/milling	US $/kg HM				100	
Conversion	US $/kg HM	40–94				
Enrichment	US $/SWU	600–957				
Fuel UOX	US $/kg HM	193–250				
Fuel MOX	US $/kg HM					5600–7700
Away-from-reactor storage	US $/kg HM		36–213	32–48		
Reprocessed UOX	US $/kg HM					6200–7300

Note: HM — heavy metal; MOX — mixed oxide; SWU — separative work unit; UOX — uranium oxide.

Reference fuel cycle cost data in 2008 US dollars are presented in Table II.8 to compare the synergistic and separate cases regarding investment in fuel cycle facilities as well calculation of levelized electricity costs for different fuel cycle options.

Enrichment, reprocessing and MOX fabrication facilities are the most capital intensive. The reference capacity is chosen as 3 million SWU per year; overnight cost is US $700/SWU for the enrichment facility, 500 t HM per year with overnight cost in the range of US $4500–6000/kg HM for reprocessing facilities, and 250 t HM per year with overnight cost in the range of US $4500–6000/kg HM for MOX fabrication facilities. These costs serve as a basis to compare different cases. The proportional increase or decrease of those costs does not lead to the relative difference in case costs.

Large commercial facilities can be deployed to realize gains from economies of scale. The most expensive fuel cycle facilities (i.e. enrichment, separation and MOX fuel fabrication facilities) are scaled to national size (national facility) for a small nuclear power programme with a few GW(e) and to an international centre size (international facility) with for the back end synergistic variant. The reference facility corresponds to a facility for a medium sized national nuclear power programme (see Table II.9). Reference data from Table II.9 is used to determine the associated scaling of costs versus size using approximation curves from Figs II.5 and II.7.

The enrichment overnight costs are estimated to range from a low of US $400/kg SWU (scaled to a facility size of 20 million SWU/year) up to US $1000/kg SWU (for a small national 0.5 million SWU/year facility).

TABLE II.8. FUEL CYCLE FACILITIES REFERENCE COSTS (IN 2008 US $)

Fuel cycle facility	Unit	Overnight cost	Service cost
Uranium	US $/kg HM	300	80
Conversion	US $/kg HM	70	10
Enrichment	US $/SWU	700	110
Fuel UOX	US $/kg HM	500	275
Away-from-reactor storage	US $/kg HM	50	200
Fuel fabrication MOX	US $/kg HM	6000/4500	1500
Fuel fabrication blanket	US $/kg HM		300
Fuel fabrication metal	US $/kg HM		2000
Reprocessing UOX	US $/kg HM	6000/4500	1500/1300
Reprocessing MOX	US $/kg HM	6000/4500	1500
Reprocessing blanket	US $/kg HM		300
Reprocessing metal fuel	US $/kg HM		2000
LWR SNF direct disposal	US $/kg HM		800
HLW direct disposal	US $/kg HM		400

Note: HLW — high level waste; HM — heavy metal; LWR — light water reactor; MOX — mixed oxide; SNF — spent nuclear fuel; SWU — separative work unit; UOX — uranium oxide.

TABLE II.9. FUEL CYCLE NATIONAL FACILITY–REFERENCE FACILITY–INTERNATIONAL CENTRE (N–R–I) COSTS (IN 2008 US $)

	Facility capacity (N–R–I)	Nuclear power (N–R–I)	Overnight cost, N–R–I	Service cost, N–R–I
Enrichment	0.5–3–20 (million SWU/year)	4–22–145 (GW(e))	1000–700–400 (US $/kg SWU)	110–110–110 (US $/kg SWU)
Fuel fabrication MOX	50–250–1500 (t HM/year)	4.5–23–140 (GW(e))	8000–4500/6000–2500/3000 (US $/kg HM)	3000–1500–750 (US $/kg HM)
Reprocessing UOX	100–500–3000 (t HM/year)	5–25–145 (GW(e))	8000–4500/6000–2500/3000 (US $/kg HM)	3000/2700–1500/1300–750/580 (US $/kg HM)
Reprocessing MOX and blanket	100–500–3000 (t HM/year)	5.7–29–170 (GW(e))	8000–4500/6000–2500/3000 (US $/kg HM)	3000–1500–750 (US $/kg HM)

The reference overnight cost of US $700/kg SWU represents the costs for a 3 million SWU/year facility. Fuel recycling and MOX fabrication facilities are sized to 3000 t HM/year and 1500 t HM/year capacities, respectively, with overnight cost in the range of US $2500–3000/kg HM. This suggests that fewer centralized facilities would be built to gain from the improved economies of scale. National based facilities are scaled to 50 t HM/year and 100 t HM/year capacities, respectively, with overnight cost of US $8000/kg HM. The reference overnight costs in the range of US $4500–6000/kg HM represents the costs for 500 t HM/year and 250 t HM/year capacities for fuel recycling and MOX fabrication facilities, respectively. Facility size is correlated to nuclear power plant installed capacity in the ranges of 4–6 GW(e), 20–30 GW(e) and 140–170 GW(e) for national, reference and international centre approaches, respectively.

The data collected is assumed to be used for evaluation of the economic impacts due to advances in technologies (introduction of fast reactor and closed fuel cycle), changing to economies of scale, cooperation among suppliers and users of nuclear fuel cycle services, and changing in uranium cost.

II.2. ELECTRICITY GENERATION COST METHOD

According to INPRO methodology, the value of energy cost determines whether or not to use the discounted cost (LUEC) model [II.24]. The model is useful for economic comparison of different types of power plant, particularly when supplemented with additional detailed information such as bond emissions, equities and other financing tools. LUEC is defined as the cost per unit of electricity generated, which is the ratio of total lifetime expenses to total expected power output, expressed in terms of a present value equivalent.

$$\mathrm{LUEC} = \frac{\sum_t \frac{\left(I_t + \mathrm{O\&M}_t + F_t\right)}{(1+r)^t}}{\sum_t \frac{E_t}{(1+r)^t}} \tag{II.1}$$

where

E_t is the electricity generation at year t;
I_t is the capital expenditures at year t;
$\mathrm{O\&M}_t$ is the O&M expenditures at year t;
F_t is the fuel expenditures at year t;

and r is the real discount rate.

The discount rate takes into account the time value of money. All values in LUEC are discounted to the power plant startup. In general, real discount rates for a government owned utility in a regulated market could be expected to vary 3–5%, for a private sector utility operating in a regulated market 5–10%, and for a private utility operating in a deregulated market 10–15% [II.24].

The LUEC includes the three components of the capital (amortization) costs (LUAC), the O&M costs (LUOM) and the fuel costs (LUFC):

$$\mathrm{LUEC} = \mathrm{LUAC} + \mathrm{LUOM} + \mathrm{LUFC} \tag{II.2}$$

In this study, LUEC costs for LWRs and fast reactors are calculated with a focus on fuel cycle components. This study uses the NEST, a Microsoft Excel and Visual Basic for Applications based spreadsheet developed by the INPRO group as the part of the Nuclear Energy System Assessment support package. It is designed for calculation of all parameters of economics envisaged in the INPRO methodology (e.g. LUEC and net present value). NEST includes examples of LUEC calculation for different nuclear reactor types with different fuel cycles, for example an LWR with an open fuel cycle or with a partially closed cycle using MOX fuel, and different types of fast reactor with a completely closed cycle. The present study uses a basic version of NEST for calculating LWR levelized unit cost as well as an advanced version of NEST for calculating LUEC for fast reactors operating in a closed uranium–plutonium fuel cycle with a given breeding ratio, based on reprocessing of spent fuel from a reactor core and blankets and multi-recycling of plutonium and uranium, and disposal of HLW from reprocessing.

Figures II.9 and II.10 illustrate levelized unit costs with discount rate of 5% for the three options considered in this study, calculated using the reference cost units for all fuel cycle steps. The options are represented by an LWR operating in once through fuel cycle, a fast reactor in closed fuel cycle fuelled by its own reprocessed plutonium, and a fast reactor fuelled by plutonium recycled from LWR spent fuel during its first three years of operation. The capital costs (LUAC) are assumed to be equal for all options, as well as the operation and maintenance costs (LUOM), with differences only in fuel cycle components.

The capabilities of NEST were extended for detailed calculation of the LUEC fuel component. Fuel cycle components are divided into uranium cost (F_U), fuel reload (F_{reload}), fuel first load (F_{FL}), spent fuel disposal (F_{SF}) for a once through fuel cycle (see Fig. II.11), and into reprocessing cost (F_R) (plutonium recovery cost), F_{reload}, F_{FL}, HLW disposal cost (F_{HLW}) for closed fuel cycle, respectively (see Fig. II.12):

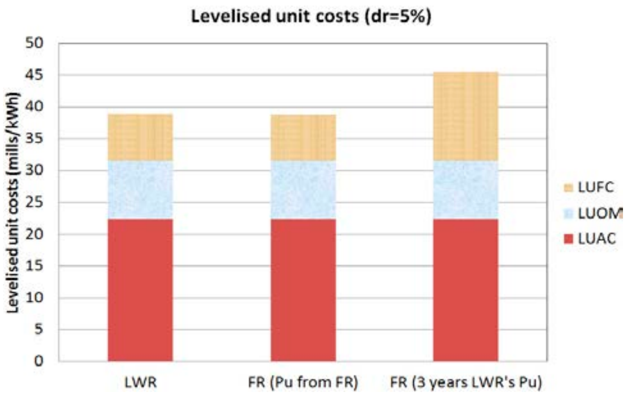


FIG. II.9. Levelized unit electricity cost, reference costs.

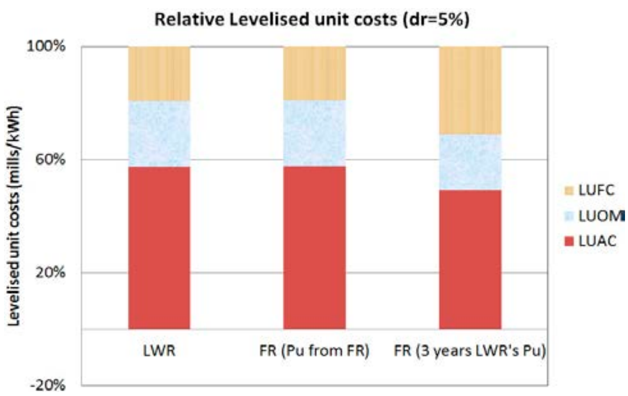


FIG. II.10. Relative levelized unit electricity cost, reference costs.

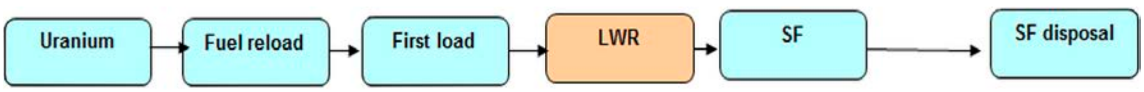


FIG. II.11. Breakdown of LUFC for once through fuel cycle based on a light water reactor.

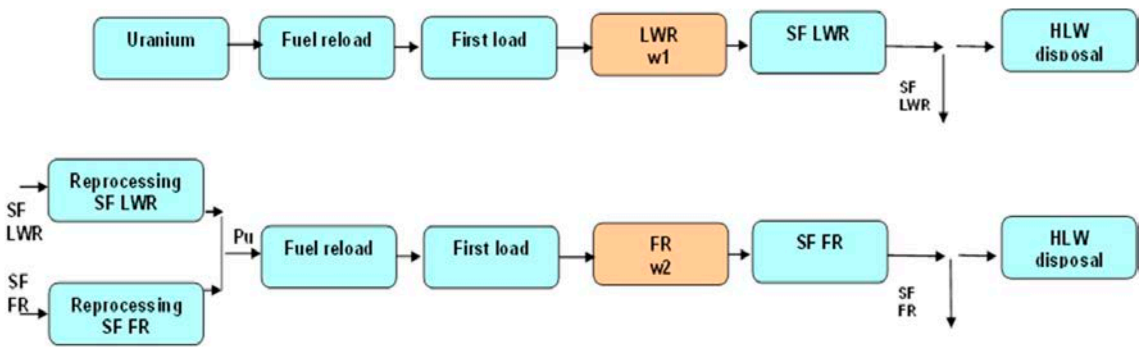


FIG. II.12. Break down of LUFC for a closed fuel cycle based on a fast reactor.

$$F_{\mathrm{LWR}} = F_{\mathrm{U}} + F_{\mathrm{reload}} + F_{\mathrm{FL}} + F_{\mathrm{SF}} \tag{II.3}$$

$$F_{\mathrm{FR}} = F_{\mathrm{R}} + F_{\mathrm{reload}} + F_{\mathrm{FL}} + F_{\mathrm{HLW}} \tag{II.4}$$

The F_{LWR} cost calculations of UOX fuel were performed using the standard formulas for mathematical mass flow calculation:

$$\text{Natural uranium cost} = \mathrm{Cost}_{\mathrm{U}} \times \frac{x_{\mathrm{enr}} - x_{\mathrm{tail}}}{x_{\mathrm{nat}} - x_{\mathrm{tail}}} \tag{II.5}$$

where

x_{enr} is the enrichment of fresh fuel;
x_{tail} is the tails assay;

and x_{nat} is the enrichment of natural uranium.

Fuel reload includes costs of conversion, enrichment and fuel fabrication for a once through fuel cycle based on LWR:

$$\text{Conversion cost} = \mathrm{Cost}_{\mathrm{Conversion}} \times \frac{x_{\mathrm{enr}} - x_{\mathrm{tail}}}{x_{\mathrm{nat}} - x_{\mathrm{tail}}} \tag{II.6}$$

$$\text{Enrichment cost} = \mathrm{Cost}_{\mathrm{SWU}} \times \left(V(x_{\mathrm{enr}}) + V(x_{\mathrm{tail}}) \frac{x_{\mathrm{enr}} - x_{\mathrm{nat}}}{x_{\mathrm{nat}} - x_{\mathrm{enr}}} + V(x_{\mathrm{nat}}) \frac{x_{\mathrm{enr}} - x_{\mathrm{tail}}}{x_{\mathrm{nat}} - x_{\mathrm{tail}}} \right) \tag{II.7}$$

where

$$V(x) = (1-2x)\ln\left(\frac{1-x}{x}\right)$$

$$\text{Fuel fabrication cost} = \mathrm{Cost}_{\text{fuel fabrication}} \frac{365 \times \mathrm{Cap} \times \mathrm{Lf}}{\mathrm{Eff} \times \mathrm{BU}} \tag{II.8}$$

$$\text{Spent fuel disposal cost} = \mathrm{Cost}_{\text{SF direct disposal}} \frac{365 \times \mathrm{Cap} \times \mathrm{Lf}}{\mathrm{Eff} \times \mathrm{BU}} \tag{II.9}$$

where

Cap is the capacity of the LWR;
BU is the average LWR fuel burnup;
Lf is the load factor;

and Eff is the thermal efficiency.

Fuel reload for a fast reactor includes cost of fuel fabrication blankets and of MOX fuel for the core:

$$\text{Fuel fabrication cost} = \mathrm{Cost}_{\text{fuel fabrication}} \frac{365 \times \mathrm{Cap} \times \mathrm{Lf}}{\mathrm{Eff} \times \mathrm{BU}} \tag{II.10}$$

where

Cap is the capacity of the fast reactor;
BU is the average fast reactor fuel burnup over gore and blankets;
Lf is the load factor;

and Eff is the thermal efficiency.

Reprocessing cost F_R is defined via plutonium cost C_{Pu}, recovered from the reprocessed spent fuel (LWR or fast reactor) plutonium concentration in fresh fuel and x_{Pu}, as:

$$F_{R} = \frac{C_{Pu} \cdot x_{Pu}}{(1+r)^{t_{pp}-t_{0}}} \tag{II.11}$$

where $t_{pp}-t_0$ is time from plutonium purchase till fuel loading in the core, and

$$C_{Pu} = \frac{C_{R} \cdot (1+r)^{t_{Pu}-t_{R}}}{(1-f_{R}) \cdot (x_{PuSF})} \tag{II.12}$$

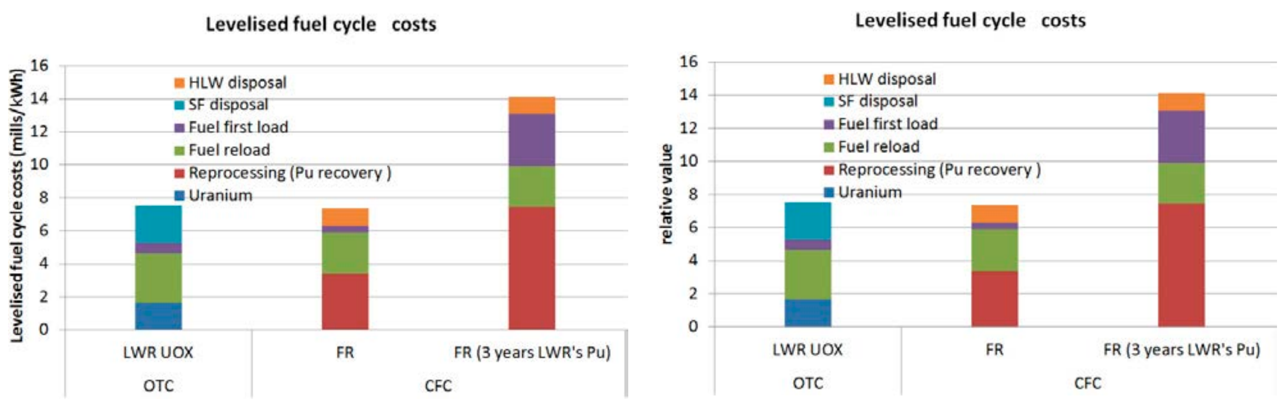
where

C_R is the cost of spent fuel unit reprocessing (in US \$/kg);
t_R is the time until reprocessing is paid after fuel discharge;
t_{Pu} is the time until plutonium is recovered after fuel discharge;
f_R is the fraction of plutonium that is not recovered during reprocessing;

and x_{PuSF} are the total plutonium isotope concentrations in the spent fuel.

Plutonium recovery cost C_{Pu} depends on total plutonium isotope concentrations in the spent fuel. Average plutonium content in LWR spent fuel (about 1%) is much less than in fast reactor spent fuel (average for core and blankets is about 10%). Therefore, the cost of plutonium recovered from LWR spent fuel can be higher than for fast reactor spent fuel even if reprocessing unit cost of latter is higher. Figure II.13 illustrates LUFC for LWR and fast reactor based on reference cost data (see Table II.8) in million/kW·h and in dimensionless form (divided by million/kW·h).

An LWR operating in a once through fuel cycle has the comparable fuel cycle component of levelized electricity generation cost of a fast reactor consuming plutonium. The fast reactor fuelled by plutonium recycled from LWR spent fuel during its first three years of operation has the highest fuel cycle cost. The main factors influencing this cost are the reprocessing cost and plutonium recovery cost (see Fig. II.14), representing more than 50% of the fuel cycle cost. This is caused by the much higher amount of spent fuel reprocessing needed to produce fuel for fast reactors from LWR spent fuel in comparison of reprocessing fast reactor spent fuel with much higher plutonium content. Therefore, the development of a fast reactor programme can face additional financial barriers as far as at first stage all new fast reactors have to pass through a stage of rather expensive fuel fabricated from LWR plutonium.



(a) (b)

FIG. II.13. Fuel cycle cost breakdown for different reactors and associated fuel cycles, (a) millions/kW·h, (b) dimensionless.

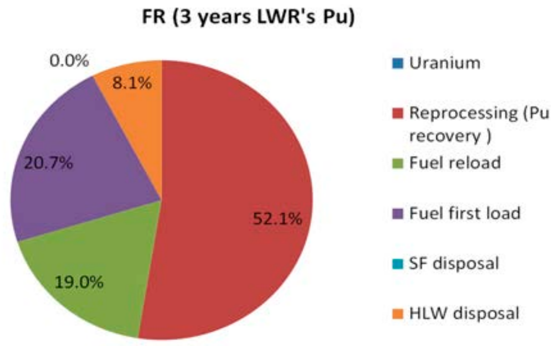


FIG. II.14. Fuel cycle cost breakdown for a fast reactor.

II.3. CALCULATION OF INVESTMENTS IN REACTORS AND FUEL CYCLE FOR SCENARIO APPROACH

To assess the economics of an NES requires not only investment in the nuclear power plant, but also investment in new capacities for fuel supply and processing. Calculation of investment in fuel cycle and reactors are based on scenarios outputs performed with the Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) tool developed by the IAEA. First, all capacity additions by region, by year and by type were calculated, and then the capital cost by region and year was calculated based on these data. The IAEA code MESSAGE can simulate the development of a complete energy system consisting of different energy sources, but it can also be used as a tool for modelling a specific NES and to compare different NES options. MESSAGE can be used for NES modelling with different level of details, from general description of energy flows conversion to detailed modelling fuel reloads and nuclear isotope flows through nuclear fuel cycle.

II.3.1. Investments in nuclear power plants

This study follows the framework developed in the GAINS study [II.25] with the assumption of an electric energy production of 1500 GW·year in 2050, 5000 GW·year in 2100, then the production growth remains flat till the end of the modelled period. NG1 and NG3 share keeps a nominal fraction as 40% and 20% in 2100 (see Fig. II.15).

Investments in nuclear power plants are calculated for the non-synergistic (separate) nominal case in NG1, based on the reference cost (Tables II.8 and II.9), for illustration. Figure II.16 shows per annum electric energy generation growth in NG1, for the separate case. The electricity energy generated by fast reactors is 10 GW, 230 GW and 1060 GW by 2030, 2050 and 2100, respectively.

Investment in nuclear power plants equals the sum of the product of overnight cost by the corresponding new nuclear power plant commissioning. A more accurate approach requires detailed cash flow per year. This study assumes uniform distribution of capital investment flow during construction time.

Added nuclear power plant capacities comprise new capacities needed to meet energy demand growth and capacities needed to replace the decommissioned ones. The latest can be calculated based on historical capacities and the nuclear power plant's lifetime. Figure II.17 shows nuclear power plant commissioning capacity for electric energy generation growth identified in Fig. II.16 for 50% of world historical capacities, assuming a 5 year construction time and a 60 year lifetime for all nuclear power plants. Blue and green columns represent LWR and fast reactor added capacities, respectively. Yellow points represent the new capacities needed to replace the decommissioned ones. The sharp growth in 2030 results from an increase in the rate of electricity generation and the start of historical capacity decommissioning. The actual commissioning curve is likely to be smoother, but the issue of replacing the decommissioned capacities while growing electricity generation remains.

Figure II.18(a) shows investments in new nuclear power plants in NG1 corresponding to the nuclear power plant commissioning presented in Fig. II.17. The reference overnight cost used for the exercise (US $3000/kW(e)) was selected for illustration purposes only. The columns for investment in LWR and fast reactor follow the commissioning columns. The red curve represents the investment distributed over the construction time (five years for all facilities). The increase of nuclear power plant commissioning in 2030 is associated with the investment

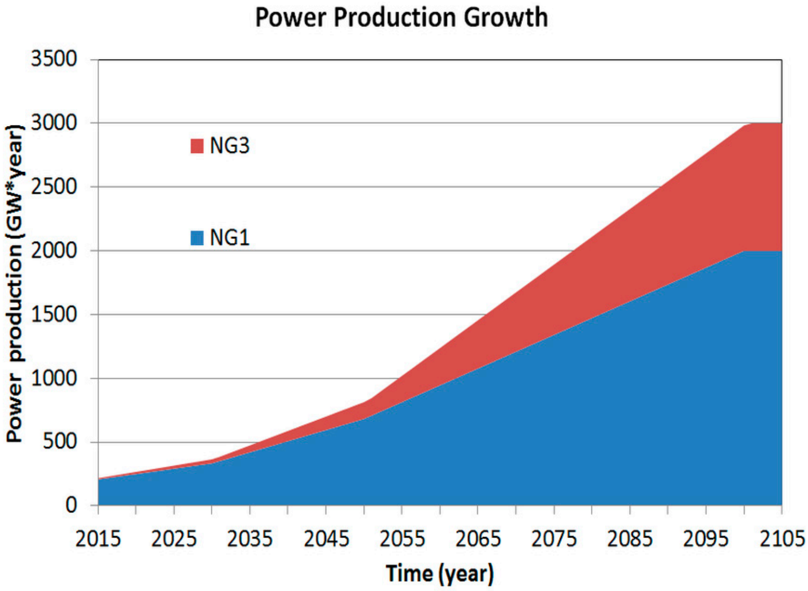


FIG. II.15. Per annum electric energy generation growth, NG1 and NG3.

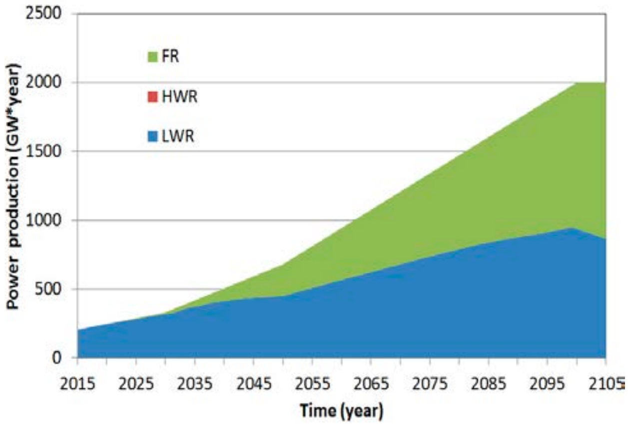


FIG. II.16. Per annum electric energy generation growth, NG1.

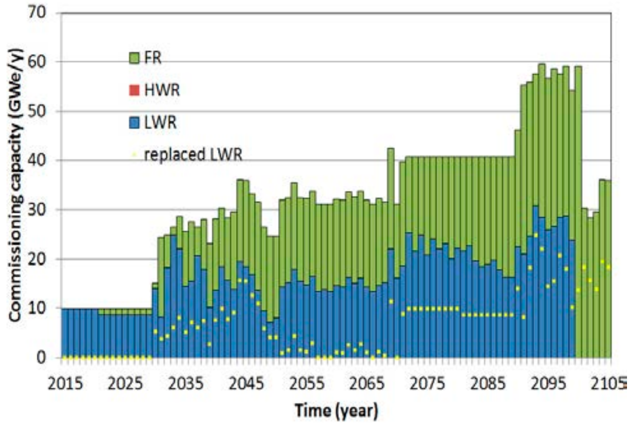
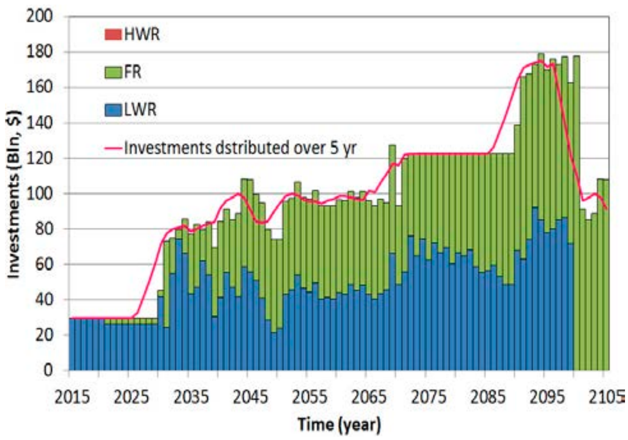
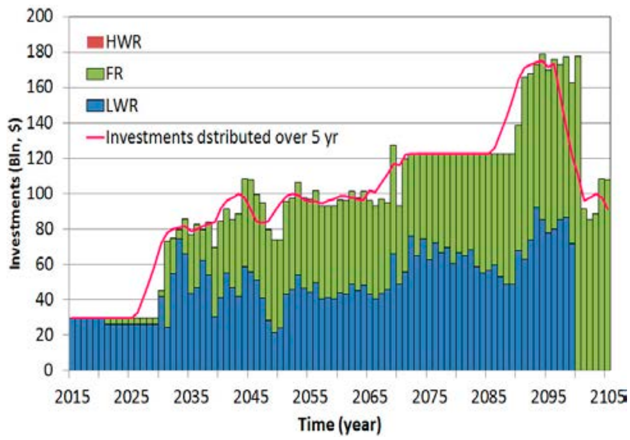


FIG. II.17. Nuclear power plant commissioning, NG1.

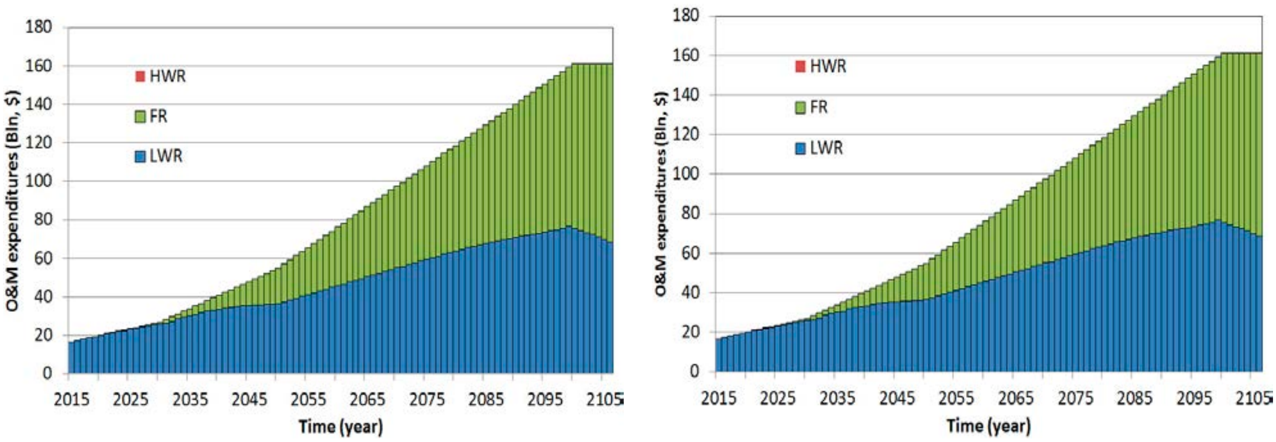


(a)



(b)

FIG. II.18. Investments in new nuclear power plants, NG1, (a) US $billions, (b) dimensionless.



(a) (b)

FIG. II.19. O&M expenditures in nuclear power plants, NG1, (a) US $billions, (b) dimensionless.

increase. Figure II.18 (b) illustrates the nuclear power plant investment in dimensionless form. Figure II.19 gives O&M expenditures in nuclear power plants in NG1, which are the sum of the product of electricity production divided by the unit of O&M cost for all reactors, in US $billion and in dimensionless form.

II.3.2. Investments in the nuclear fuel cycle

The main fuel cycle facilities under consideration include the following process stages: mining and milling, conversion, enrichment, UOX fuel fabrication, MOX fuel fabrication, UOX reprocessing, MOX reprocessing and long term spent fuel storage. The final stages (final disposal of spent fuel and HLW) are assumed to have similar investments and do not impact comparison results.

Fuel cycle investments in this study follow the same approach as investments in nuclear power plants. Investments in a particular nuclear fuel cycle facility are calculated as the sum of capital investment uniformly distributed over construction time (5 years for all facilities). Lifetimes are assumed to be practically unlimited except for reprocessing facilities, which have a 60 year lifetime. The load factor of fuel cycle facilities is assumed to be 1. The total investments in fuel cycle scheme represent the sum of investments corresponding to each stage. Investment in the nuclear fuel cycle is represented in dimensionless form.

II.3.3. Mining and milling

Figure II.20 shows per annum natural uranium requirements corresponding to the electric energy generation growth, in NG1, for the separate case. Added mining capacities are calculated based on these requirements. The requirements are expected to increase from 50 kt U in 2015 to about 100 kt U by 2035, which will require an average of 2 kt U of added mining capacities. The requirements remain the same in the medium term (2035–2050), so there is no need for new mining capacities during this period. For long term period (after 2050), the uranium requirements will increase, which will require an average of 4 kt U of added mining capacities. The investment pattern follows the added mining capacities, with investments around 0.5 and 1 units in the short term (by 2030) and long term (after 2050), respectively, but low investment in the medium term (2030–2050) (see Fig. II.21).

II.3.4. Conversion

The conversion requirement is defined by annual uranium requirement, including natural as well as recycled uranium from reprocessing (see Fig. II.22). Therefore, added conversion capacities follow the trends of added mining capacities. Investments are around 0.1 and 0.2 units in the short term (by 2030) and long term (after 2050), respectively. There is stepwise uranium consumption growth in the medium term, which causes erratic decreased investment in conversion facilities (see Fig. II.23). Investment in conversion facilities is significantly less than investment in mining facilities.

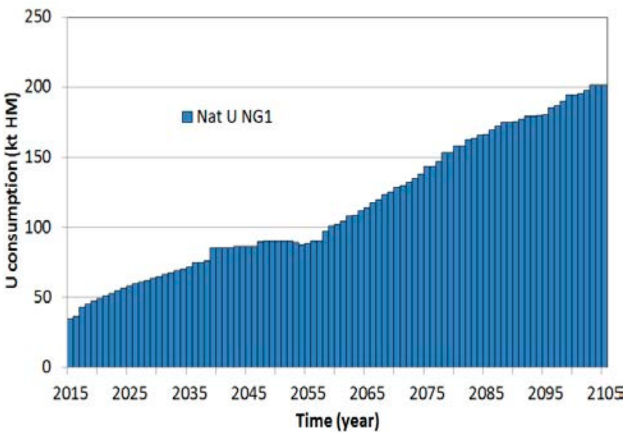


FIG. II.20. Annual natural uranium requirements.

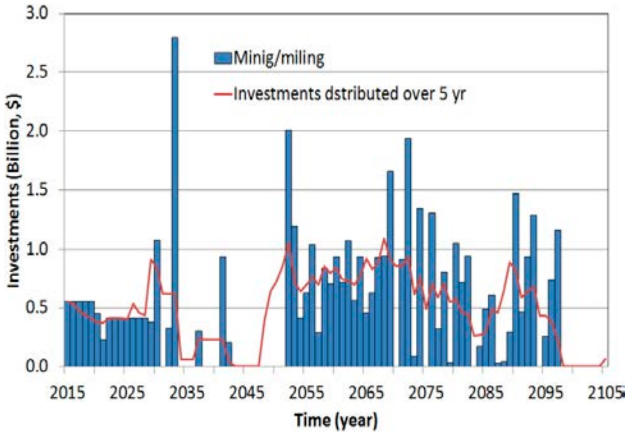


FIG. II.21. Investments in uranium mining and milling capacities (dimensionless).

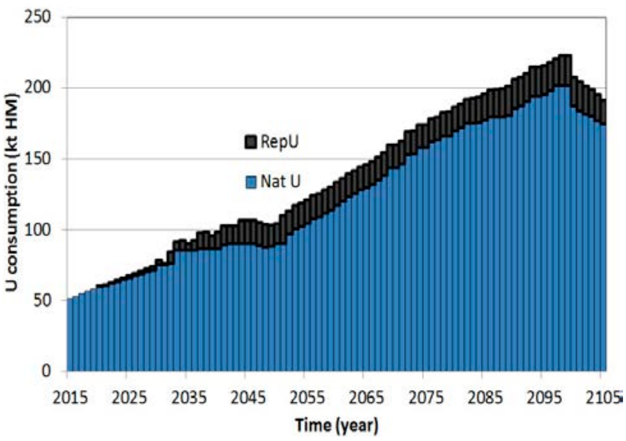


FIG. II.22. Annual uranium requirements.

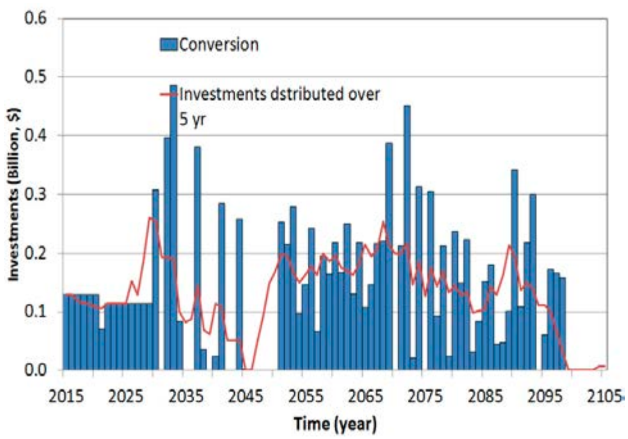


FIG. II.23. Investments in conversion facilities (dimensionless).

II.3.5. Enrichment

Figure II.24 shows SWU requirements in NG1 for the separate case, including enrichment of natural and reprocessed uranium. Historical capacities are assumed to be half of global capacities (52 M SWU). Starting from 2.2 M SWU in 1961, the global capacity reached 26 M SWU in 2008. The lifetime of a SWU facility is assumed to be 100 years, so the first replacement facilities will be commissioned in 2065. New SWU capacity is proportional to new conversion capacities in the short and medium terms. Capacity will be around 0.5 units in the short term, it will jump to about 3 units in 2030, and then it will decrease to zero (see Fig. II.25). The replacement of historical capacities (starting in 2065) will follow the investment curve up to 3 units. Investments in enrichment facilities are comparable with investments in mining facilities.

II.3.6. Fuel fabrication

Fuel fabrication requirements compose the UOX and MOX fuel types, as shown in Fig. II.26. Historical capacities represent half of the global UOX capacities (7 kt HM), which exceed the existing requirements in UOX fuel. Investments in UOX and MOX fuel fabrication facilities are given in Figs II.27 and II.28.

New capacities for LWR UOX fuel may need to be commissioned starting from 2020. The common pattern of investments in UOX facilities follows the main features of investments in other front end facilities, which are themselves correlated with the growth of electric energy generation in NG1. Investments in UOX fuel fabrication are comparable with investments in conversion, and do not contribute to the total fuel cycle investments. The UOX

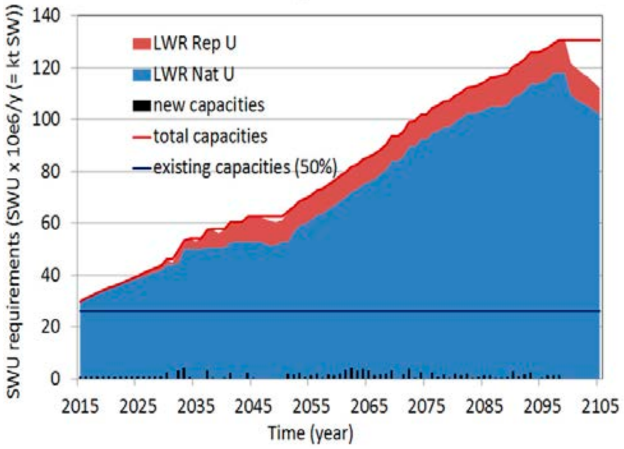


FIG. II.24. Separative work unit requirements.

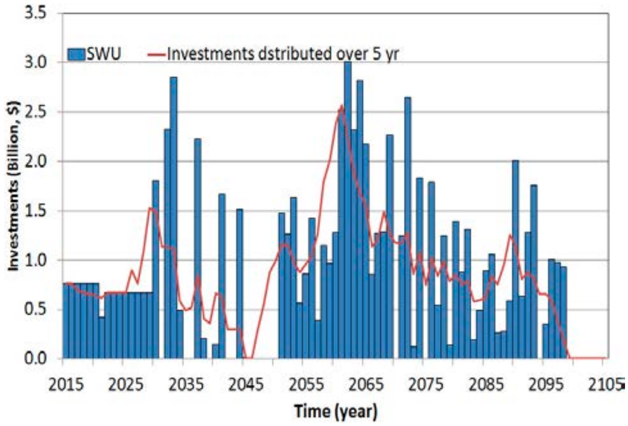


FIG. II.25. Investments in enrichment facilities (dimensionless).

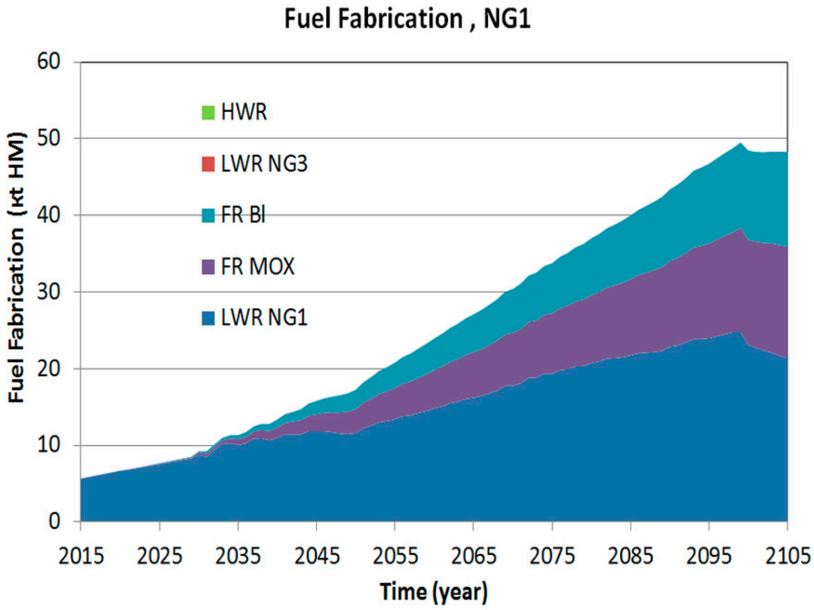


FIG. II.26. Fuel fabrication requirements.

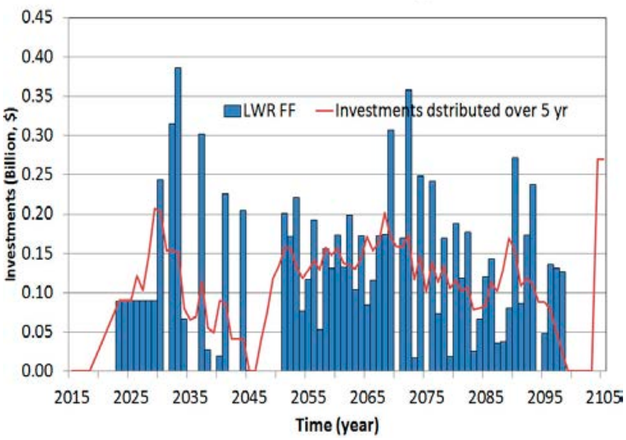


FIG. II.27. Investments in light water reactor fuel facilities (dimensionless).

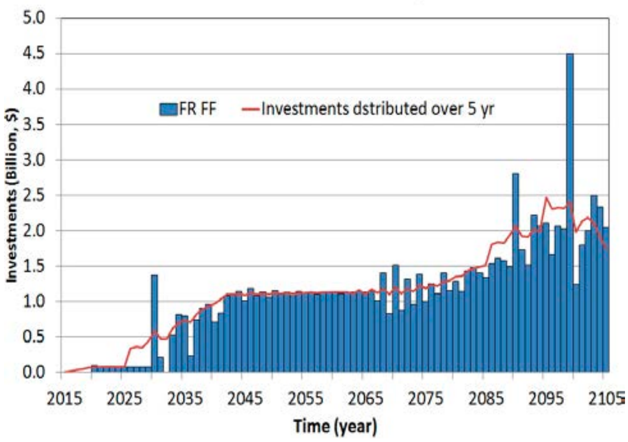


FIG. II.28. Investments in fast reactor fuel facilities (dimensionless).

fuel requirements are significantly higher than the MOX fuel requirements. The same observation is true for added capacities. However, investments in MOX fuel fabrication facilities are several times higher than investments in UOX fuel fabrication facilities, and contribute significantly to the total fuel cycle investments, in the medium and long terms. One unit is needed in the medium term, increasing the requirements to two units by the end of the century.

II.3.7. Long term storage

Accumulation of UOX spent fuel in long term storage and associated investments in storage facilities are shown in Figs II.29 and II.30. Spent fuel accumulation starts from about 85 kt HM, which is half of historical spent fuel amount from LWRs, as calculated in Ref. [II.25]. Spent fuel storage achieves maximum capacity of 160 kt HM by 2035, and then decreases until it is fully depleted around 2075. By then, all LWR spent fuel available for reprocessing is reprocessed without transfer to long term storage. Storage investments are not very significant in comparison with other fuel cycle investments (around 0.2 units), but they need to be undertaken in the short term, by 2025.

II.3.8. Reprocessing

Reprocessing loads for spent fuel from LWRs and fast reactors are shown in Figs II.31 and II.32, respectively. The reprocessing capacity of LWR spent fuel is assumed to be limited at a rate of up to 850 t/year, which is sufficient to process the available spent fuel till 2050. After 2050, new LWR reprocessing capacity is possible,

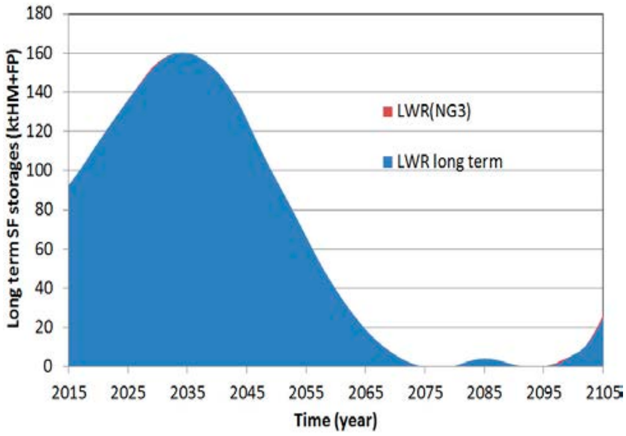


FIG. II.29. Long term spent fuel storages.

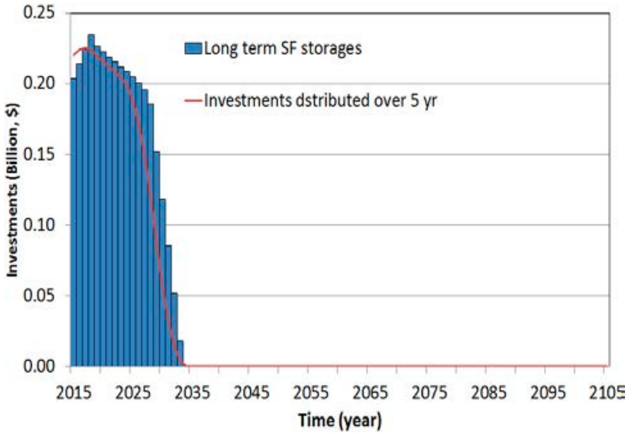


FIG. II.30. Investments in long term storage (dimensionless).

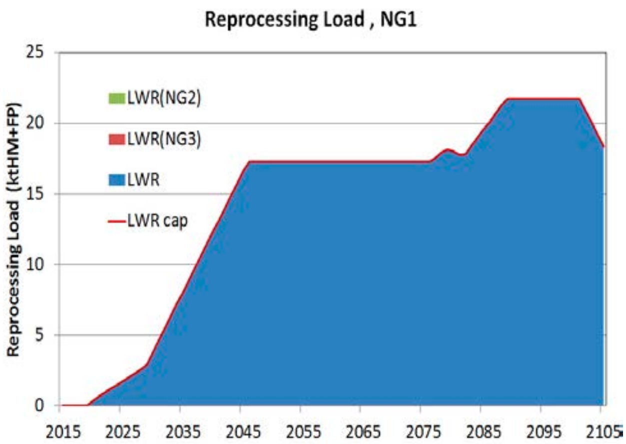


FIG. II.31. Light water reactor, spent fuel reprocessing requirements.

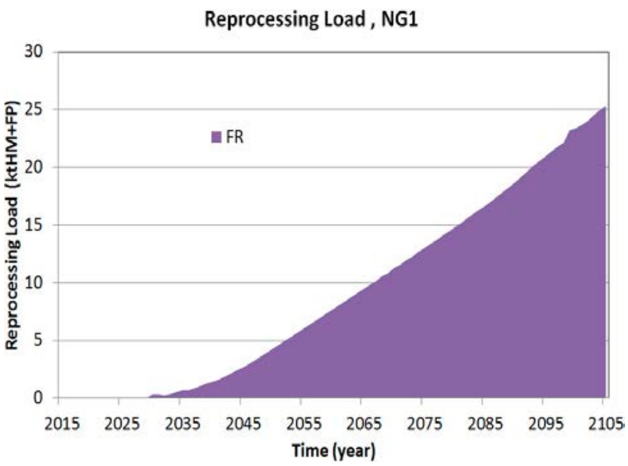


FIG. II.32. Fast reactor, spent fuel reprocessing requirements.

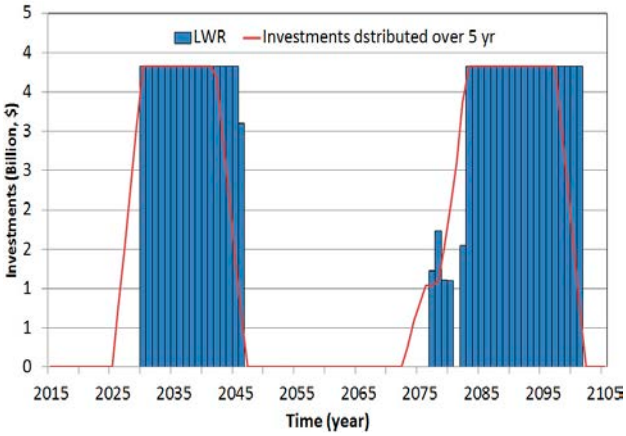


FIG. II.33. Investments in light water reactor, fuel reprocessing facilities (dimensionless).

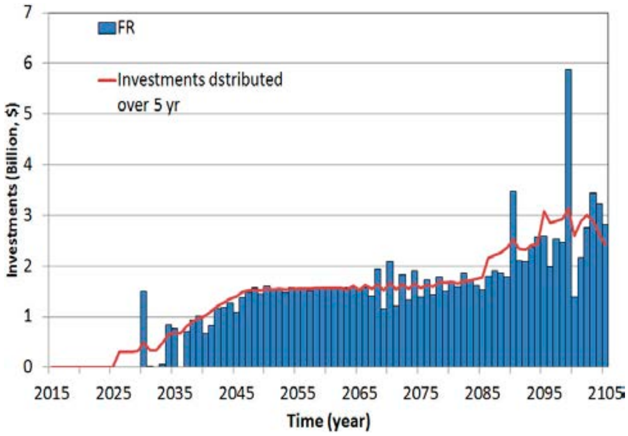


FIG. II.34. Investments in fast reactor, fuel reprocessing facilities (dimensionless).

at a rate of up to 3000 t/year. The LWR reprocessing capacity steadily increases until 2045, achieving a rate of about 17 kt/year, this rate being maintained till 2085, followed by further growth in reprocessing load. Thus, there are periods of rapid construction for added capacity during 2030–2045 and from 2085 till the end of century. Consequently, investments in LWR spent fuel reprocessing plants follow the same growth periods illustrated in Fig. II.33. The most challenging period is the medium term (2030–2045), which is characterized by the highest investment demands for construction of LWR spent fuel reprocessing plants. The last high investments period corresponds to the increase of reprocessing load and replacement of reprocessing plants after 60 years of operations.

Investments calculation takes into account historical reprocessing capacities. Current commercial reprocessing amounts to a nominal capacity of 40 000 t HM/year, assured by AREVA's La Hague plant (in France), Sellafield (in the United Kingdom), the Mayak site (in the Russian Federation), and Rokkasho Reprocessing Plant (in Japan).[1] This capacity can meet reprocessing requirements for LWR spent fuel in the short term (2020–2030).

Figures II.32 and II.34 show the fast reactor, spent fuel reprocessing load and investments in fast reactor fuel reprocessing facilities, respectively. The reprocessing capacity gradually climbs up to 25 kt/year by the end of century. The reprocessing capacity was set as unlimited. The investments achieve the level of 1.6 units from 2030 to 2045, maintain this level till 2085, and then increase up to 3 units by the end of century.

Figure II.35 summarizes the investments in all fuel cycle stages including mining and milling, conversion, enrichment, UOX fuel fabrication, MOX fuel fabrication, UOX reprocessing, MOX reprocessing and long term spent fuel storage for the NG1, in the separate case. Investments in LWR spent fuel reprocessing represent the most significant contributor to the total fuel cycle investments; reprocessing plants can be a serious barrier to transitioning towards innovative NESs in the medium term.

Assuming an optimal use of fuel cycle facilities on full capacity during their entire lifetime, and reference size facilities corresponding to a large national nuclear power programme, the investments in the fuel cycle are only about 10% of the investments in nuclear power plants. Construction of small national facilities for a small nuclear programme can significantly increase the cost of the fuel cycle.

II.3.9. Discounted investment costs

Discounted investment cost takes into account time value of money. Total net present investment cost of implementation (NPIC) for different fuel cycle facilities in the scenario under consideration is given by Eq. (II.13), where I_{FC_t} is the capital fuel cycle facility expenditures at year t and r is the real discount rate:

$$\mathrm{NPIC} = \sum_t \frac{\left(I_{\mathrm{FC}\_t}\right)}{\left(1+r^t\right)} \tag{II.13}$$

[1] See http://infcis.iaea.org

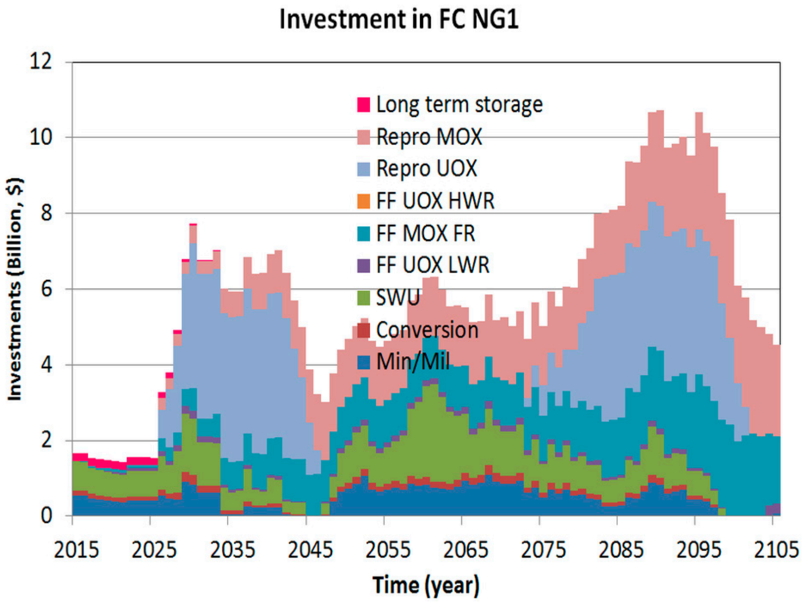


FIG. II.35. Nuclear fuel cycle investments in NG1 (dimensionless).

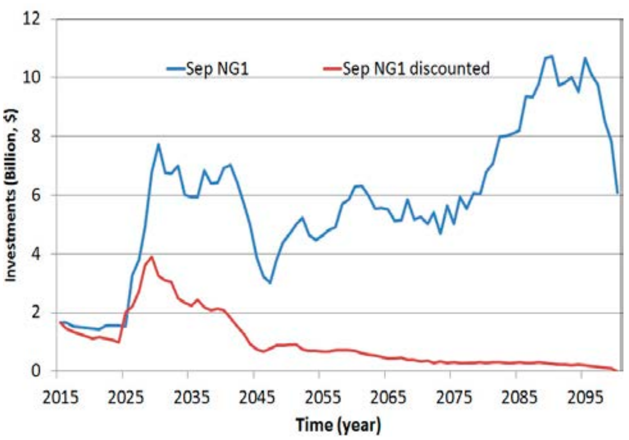


FIG. II.36. Annual investment in fuel cycle of NG1 (dimensionless).

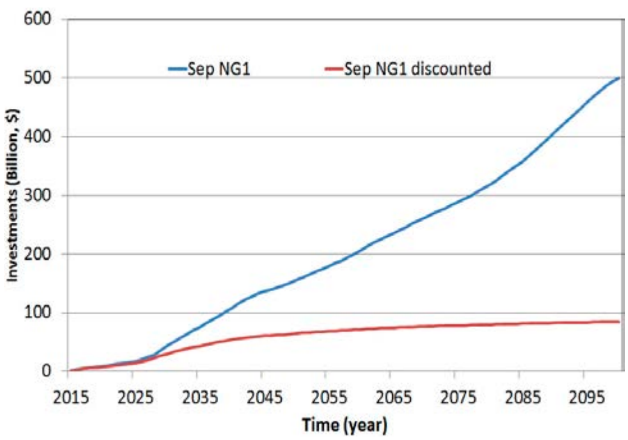


FIG. II.37. Total investment in fuel cycle of NG1 (dimensionless).

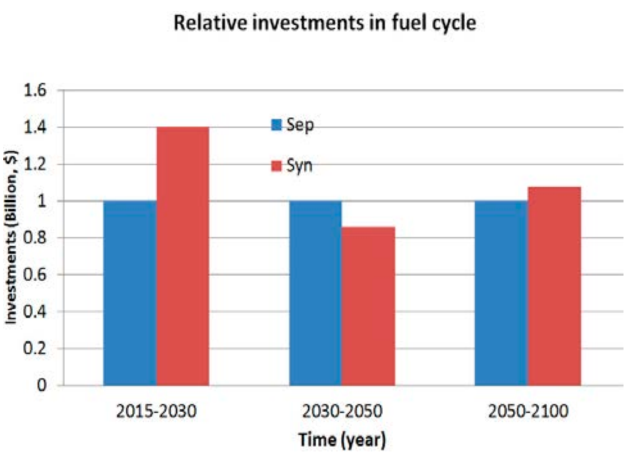


FIG. II.38. Relative investment in fuel cycle for separate and synergistic cases.

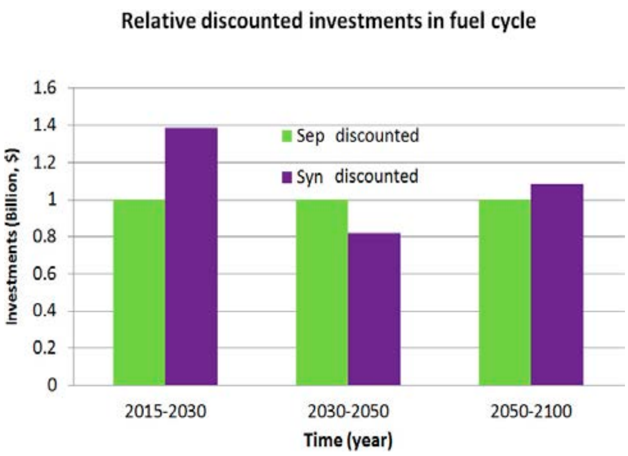


FIG. II.39. Relative discounted investments in fuel cycle for separate and synergistic cases.

Figure II.36 illustrates investments in fuel cycle facilities for the separate NG1 scenario considering 0% discount rate (undiscounted) and 5% discount rate, respectively. Total discounted fuel cycle investments for 0% and 5% discount rates are shown in Fig. II.37.

Economic analysis that uses the time value of money will increase the relative contribution of the early fuel cycle facilities construction schedule and facility scale. Discounting decreases the relative costs for construction at the end of modelling time horizon.

Figures II.38 and II.39 illustrate possible comparison of fuel cycle investments for the separate (non-synergistic) and synergistic cases in a relative form, with synergistic results divided by those for the separate case.

II.3.10. Note on levelized unit energy cost, and first-of-a-kind and RD&D costs

In addition to LUEC, in-depth economic assessment of transition scenarios should take into consideration a dynamic analysis covering electricity generation cost changing over time. Estimation of the evolution of generation costs C can be performed as $C = \Sigma(\mathrm{sh}_i \times \mathrm{LUEC}_i)$, where sh_i is the share of technology i and LUEC_i is the corresponding cost.

The first comparison of considered cases was based on a simplified approach, which initially assumed that the analysis could substitute *N*th-of-a-kind (NOAK) for first-of-a-kind (FOAK); if NOAK is not a mutually beneficial scenario then it is unlikely that FOAK will be either. According to reported experiences, the FOAK plants are 15–55% more expensive than the subsequent serial units [II.14, II.15]. Building on the same site is usually cheaper than building a nuclear power plant with a single reactor, due to better construction work organization, learning effects, larger volumes of plant equipment orders, and other factors. The competitiveness of new technologies (such as fast reactors and the associated fuel cycle) with existing technologies might increase with technology progress induced by the series and learning effects.

A more detailed economic assessment of transition scenarios should also include RD&D costs for reactor and fuel cycle facilities.[2] This requirement would add specific features to the analysis of economic viability of the NES by exploring possibilities for the introduction of new innovative NES capacity in national and global markets. The GAINS study illustrated that, for a timely return on the RD&D investments, the innovative NES components should have a market of a certain capacity (~30 GW(e)); otherwise, RD&D expenditures are not justified, since they will not be recovered for more than a century.

More detailed analysis performed on the system level examined the effects of scale, timing and pace of RD&D efforts, and the buildup of new nuclear capacities based on innovative NESs, including fast reactors and closed fuel cycles [II.26]. This study identified a simple correlation between the scale of RD&D cost to be spent for transition to the innovative NES and minimal rate of the innovative NES deploying, which indicates that fast reactors could be involved in the optimal expansion strategy under this cost (or lower cost). The study also concluded that main trajectory in implementation of the innovative NES market driven strategies is to share innovative NES RD&D costs among a group of countries in order to reduce the burden on individual countries while expanding new capacities and creating demand for innovative NESs (fast reactors)[3]. In this way, larger markets can support a mutually beneficial strategy by sharing the benefits of new technologies, thus recovering the RD&D costs.

II.4. NUCLEAR ENERGY SYSTEM SIMULATION TOOLS

Most of key indicators used in the study were calculated with nuclear energy simulation tools. The applied tools include MESSAGE and Dynamic Energy System — Atomic Energy (DESAE) codes available from IAEA and national tools such as COSI, FAMILY and TEPS. The GAINS publication [II.25] introduces and compares the features of the analysis codes owned by the IAEA and Member States, and provides cross-check analysis results for a few samples of future nuclear fuel cycle scenarios. Cross-check calculations were performed for three scenarios: two once through fuel cycle scenarios (BAU[4] and BAU+) using only thermal reactors (LWR and HWR for the BAU

[2] It should be noted that these costs are not for the customer utility, and only partially for the vendor, the other part being borne by a government, not necessarily from the same country as the customer utility.

[3] It may be true for general R&D, while more detailed results are typically considered to be of commercial value and not shared anymore.

[4] Business as usual.

scenario, and LWR, HWR and advanced LWR for the BAU+ scenario), as well as a plutonium recycle scenario based on thermal reactors and a break-even fast reactor with a breeding ratio of 1.0. The cross-check results and the analysis of the calculations lead to the following conclusions.

There is no significant difference between the codes for the BAU scenario based on existing LWRs and HWRs. Sample analyses for a set of homogeneous cases exhibited similar trends for nuclear material requirements. In the plutonium recycle scenario, different results could be obtained between the codes depending on how they treat approximation of the isotopic vectors of available plutonium. In long term scenario studies, however, the effects on the critical indicators, such as possible fast reactor share and cumulative uranium demand, become small and do not produce significant differences.

In addition, some national codes have been benchmarked against other codes, including benchmarking efforts from the Massachusetts Institute of Technology [II.27] and the OECD Nuclear Energy Agency [II.28]. The benchmarking results and the analysis of the calculations concluded that the general trends observed for each code are the same for the scenarios calculated in the benchmark. Some differences appear during the deployment of fast reactors owing to differences in the physical models: how the decay of heavy nuclides is taken into account in the interim storage facilities; differences in depletion; and differences in equivalence calculations for plutonium and the fraction of minor actinides in the fresh fuel. Cross-check studies using IAEA and national tools generally confirmed the applicability of the codes for the NES strategy long term analysis and highlighted the importance of further improvements of code capabilities to model and analyse the transition scenarios.

II.5. CONCLUSION

For the assessment of dynamic NES evolution scenarios, SYNERGIES followed the recommendations from GAINS, INPRO methodology, and suggestions from the participants, and used two key indicators for economics, namely the electricity generation cost (LUEC) and the total investments. INPRO methodology for the area of economics provides an assessment methodology and the NEST tool can estimate electricity generating costs as well as some other figures of merit.

The LUEC model is commonly used for general economic comparison of different types of power plant, particularly when a small amount of detailed information is added. The present study used the basic version of NEST for calculation of LUEC for LWR and the advanced version of NEST for calculation of LUEC for a fast reactor operating in closed uranium–plutonium fuel cycle with a given breeding ratio. Calculations were based on reprocessing of spent fuel from a reactor core and blankets, multi-recycling of plutonium and uranium, and disposal of HLW from reprocessing. As transition scenarios can be based on different technologies with different LUEC values, this parameter does not reflect the scenario approach specific features. In addition to LUEC, in-depth economic assessment of transition scenarios should take into consideration the total discounted cost and a dynamic analysis covering electricity generation costs changing over time.

Investment in reactors and fuel cycles based on scenario approach adds specific features to the analysis of the NES economic viability. Calculation of investment in the nuclear power plant and in new capacities for fuel supply and fuel processing are based on scenarios outputs performed using the MESSAGE tool. The heterogeneous model for NG1, NG2 and NG3 country groups is the basis to explore cooperation between groups (synergistic) and separate group development (non-synergistic) cases. Capacity additions were calculated by region, year and type. Based on these data, capital cost was calculated by region and year. This approach allows assessing the benefits and challenges of cooperation between country groups representing technology holders and users. For example, the approach can quantitatively show how an international centre for fuel reprocessing/fabrication can facilitate transition to an NES based on fast reactors and also provide benefits related to sharing of long term storage. A more comprehensive economic assessment of transition scenarios should take into consideration total (discounted) cost including investments and O&M costs. The more detail economic assessment of transition scenarios should also include RD&D for reactor and fuel cycle facilities, as well as FOAK nuclear installations.

The necessary nuclear fuel cycle input data for the NES for the analysis in the SYNERGIES collaborative project were collected based on the available references. The fuel cycle was considered to be represented by following facilities: mining, milling, conversion, enrichment, fuel fabrication, spent fuel long term storage, spent fuel disposal, spent fuel reprocessing and reprocessed products storage with their technical and economic data (capital costs, capacities, load factors and lifetimes). The data collected might not reflect the actual industrial figures. For the comparative economic analysis, the most important is to use a consistent set of economic data with appropriate proportion of fuel costs, rather than absolute values. If these costs proportionally increase or decrease, the percentage difference in cases costs will be the same. It is fully recognized that the data are subject to change in the future and should be updated when new information becomes available.

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Appendix III

SHORT DESCRIPTION OF THE GAINS APPROACH FOR ASSESSING TRANSITION SCENARIOS TO SUSTAINABLE NUCLEAR ENERGY SYSTEMS

III.1. BACKGROUND

The analytical framework for analysis and assessment of transition scenarios to sustainable nuclear energy systems (NESs) has been developed in the IAEA and International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) collaborative project Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS) and furthered in the IAEA/INPRO collaborative project Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES). It features a heterogeneous world model to consider specific fuel cycle development strategies countries may pursue. The model simulates the dynamics of global nuclear energy development and allows the identification and evaluation of areas of potential cooperation among countries. The GAINS analytical framework was applied and furthered in SYNERGIES collaborative project with the objectives of modelling the various forms of collaboration, assessing benefits and challenges relevant for collaboration, and identifying collaborative scenarios and architectures ensuring a ‘win-win’ strategy for both suppliers and users of peaceful nuclear energy technologies.

In the following, a short description of the GAINS approach for assessing transition scenarios to sustainable NESs will be provided, as used in SYNERGIES case studies at the global and regional levels. The GAINS framework includes:

— Long term projections for nuclear power evolution;
— Transition scenarios from the current to future NESs with thermal and fast reactors and closed nuclear fuel cycles;
— Internationally verified data on reactors and associated nuclear fuel cycles as needed for material flow analysis and comparative economic evaluations;
— The IAEA models and tools for material flow simulation complementary to similar national instruments;
— The agreed metrics for transitions scenario analysis and assessment and the templates for results presentation and analysis, including the results of sample scenario studies.

III.2. LONG TERM NUCLEAR ENERGY DEMAND SCENARIOS

The GAINS framework includes two long term nuclear energy demand scenarios based on the overviewed projections of the Intergovernmental Panel on Climate Change (IPCC) and the IAEA. These nuclear energy demand scenarios can serve as reference points in the global nuclear system analyses. The high nuclear energy demand scenario is a variant of the medium expectation of the IPCC reports on emission scenarios. In this scenario, global annual nuclear energy generation reaches approximately 1500 GW·year by the mid century and 5000 GW·year by 2100. The moderate nuclear energy demand scenario assumes approximately 1000 GW·year by mid century and 2500 GW·year by the end of the century, respectively. The evolution curves present the three distinct growth periods. Each growth period is modelled by linear growth to reach the specific level of generation by the end of the considered period:

(a) 2009–2030: 600 GW·year for the moderate case and 700 GW·year for the high case.
(b) 2031–2050: 1000 GW·year for the moderate case and 1500 GW·year for the high case.
(c) 2051–2100: 2500 GW·year for the moderate case and 5000 GW·year for the high case.

III.3. HETEROGENEOUS WORLD MODEL

Most studies on the future of global nuclear energy are based on a homogeneous model applied for the nuclear energy worldwide. This approach does not take into account national preferences and possibilities. The homogeneous world model describes a convergent world with rapid changes towards global solutions for economic, social and environmental challenges. The opportunities facilitating creation of the global and regional nuclear architecture, such as unification of reactor fleet, infrastructure sharing, arrangement of multinational regional fuel cycle centres, innovative approaches to financing and licensing have to be taken into account in the development of this storyline.

In addition to the homogeneous world model, GAINS has developed a heterogeneous model comprising groups of non-geographical, non-personified (NG) countries with differing fuel cycle strategies. This model can provide a more realistic analysis of transition scenarios to global innovative NES architecture. It can also be used to illustrate the global benefits of introducing innovative nuclear technologies without exposing the majority of countries to the financial risks and other burdens associated with the development and deployment of these technologies.

The heterogeneous world model developed in the GAINS collaborative project involves groups of nuclear energy countries with different strategies for spent nuclear fuel management. NG1 countries group pursues a general strategy to recycle used fuel. This group plans to build, operate, and manage used fuel recycling facilities and permanent geological disposal facilities for highly radioactive waste, and complement them with fast reactors. NG2 countries group follows a strategy either to directly dispose the used fuel, or to reprocess the used fuel abroad. This group plans to build, operate and manage permanent geological disposal facilities for highly radioactive waste (in the form of used fuel and reprocessing waste) or it works synergistically with another group to have its fuel recycled. NG3 countries group has a general strategy to use fresh fuel supplied from abroad and to send used fuel abroad for either recycle or disposal. This group has no plans to build, operate and manage used fuel recycling facilities or permanent geological disposal facilities for highly radioactive waste.

The methodology applied in the analysis does not assign individual countries to groups, but allocates a fraction of future global nuclear energy generation to each group as a function of time to explore ‘what if’ scenarios. The number of groups and the composition of each group can be altered to meet a particular analysis need.

The homogeneous synergistic world projection involves full cooperation between different parts of the world and also uniform technology application. The heterogeneous world projection involves either no cooperation (non-synergistic case) or different degrees of cooperation between groups of countries with implementation of different technologies and different fuel cycle strategies (synergistic case), as illustrated by Fig. 2.3, in Section 2.5.

Until 2008, the heterogeneous framework base cases assume that 50% of world nuclear power generation is in the recycling fuel cycle group (NG1) and 50% in the once through fuel cycle group (NG2). heavy water reactor (HWR) fuel is assumed not to be recycled and therefore 100% of the HWRs are in NG2. This results in more light water reactors (LWRs) in NG1 than in NG2. For the non-synergistic case, no movement of fuel (fresh or used) occurs between NG1 and NG2. This imposes a limitation on the amount of LWR spent fuel available in NG1 for starting fast reactors. The heterogeneous synergistic framework cases build on the non-synergistic cases. All of the primary input parameters are the same. The key difference consists in allowing the movement of material between the NGs (synergism), an action that may result in improving the ability of each group to follow their selected fuel cycle strategies.

For the framework base cases, the NG3 group is assumed to follow a strategy to limit infrastructure investments by only building reactors and obtaining fuel cycle services from NG1 and NG2. This includes front end services of mining, converting and enrichment of uranium and fabrication of fresh LWR fuel, and back end services of taking back used LWR fuel after the required cooling period. The only movement modelled is the shipment of fresh and cooled spent fuel. NG3 benefits by not having to develop, site and construct nuclear fuel cycle facilities, including those related to the disposition of highly radioactive spent fuel. For simplicity, in the framework base cases, NG1 and NG2 equally share the fuel cycle services for NG3, each providing 50% of the fresh fuel and taking back 50% of the spent fuel. In this scenario, any waste generated by reprocessing of the NG3 spent fuel for use in reactors in NG1 is kept in NG1.

III.4. ARCHITECTURES FOR NUCLEAR ENERGY SYSTEMS

Different types of NES architecture were defined and then analysed in order to evaluate the effect of implementation of innovative technologies and assess their impact on the key indicators. A homogeneous business as usual (BAU) scenario based on pressurized water reactors (PWRs) (94% of power generation) and HWRs (6% of power generation) operated in a once through fuel cycle was considered, for which the world was modelled as a single NG. A variant of this scenario included the introduction of an advanced PWR replacing conventional PWR technology (referred to as the BAU+ scenario). Homogeneous (single group) world scenarios for a closed fuel cycle using thermal and fast reactors (BAU fast reactor) for comparison with the above mentioned BAU and BAU+ scenarios, have been considered. Another interesting scenario taken into consideration was a hybrid heterogeneous architecture scenario comprising a once through fuel cycle strategy in the NG2 group, a closed fuel cycle strategy in the NG1 group and use of thermal reactors in a once through mode in the NG3 group. Other innovative scenarios using the homogeneous world model were also considered, including those with the construction of fast spectrum reactors or thermal spectrum HWRs using the thorium fuel to reduce natural uranium requirements, and those with the reduction of minor actinides using accelerator driven systems or molten salt reactors.

Figure III.1 provides an example of the flow chart for a combined once through fuel cycle and fast reactor closed fuel cycle system. As shown in the figure, the once through fuel cycle system consists of uranium mining, conversion, enrichment, depleted uranium storage, fuel fabrication, nuclear power plant operation, spent fuel storage at the nuclear power plant and long term spent fuel storage. In the case of HWRs, the steps of conversion, enrichment and depleted uranium storage do not exist because HWRs use natural uranium as the fuel.

In comparison with BAU or BAU+, the combined system presented in Fig. III.1 has additional reprocessing facility for the recycle of plutonium, minor actinides and uranium. For the fast reactor closed fuel cycle, a radioactive waste management facility is considered. The reprocessed uranium from LWRs or advanced LWRs can be used as the feeding material for re-enrichment or the matrix uranium for the fast reactor driver fuel and HWR fuel.

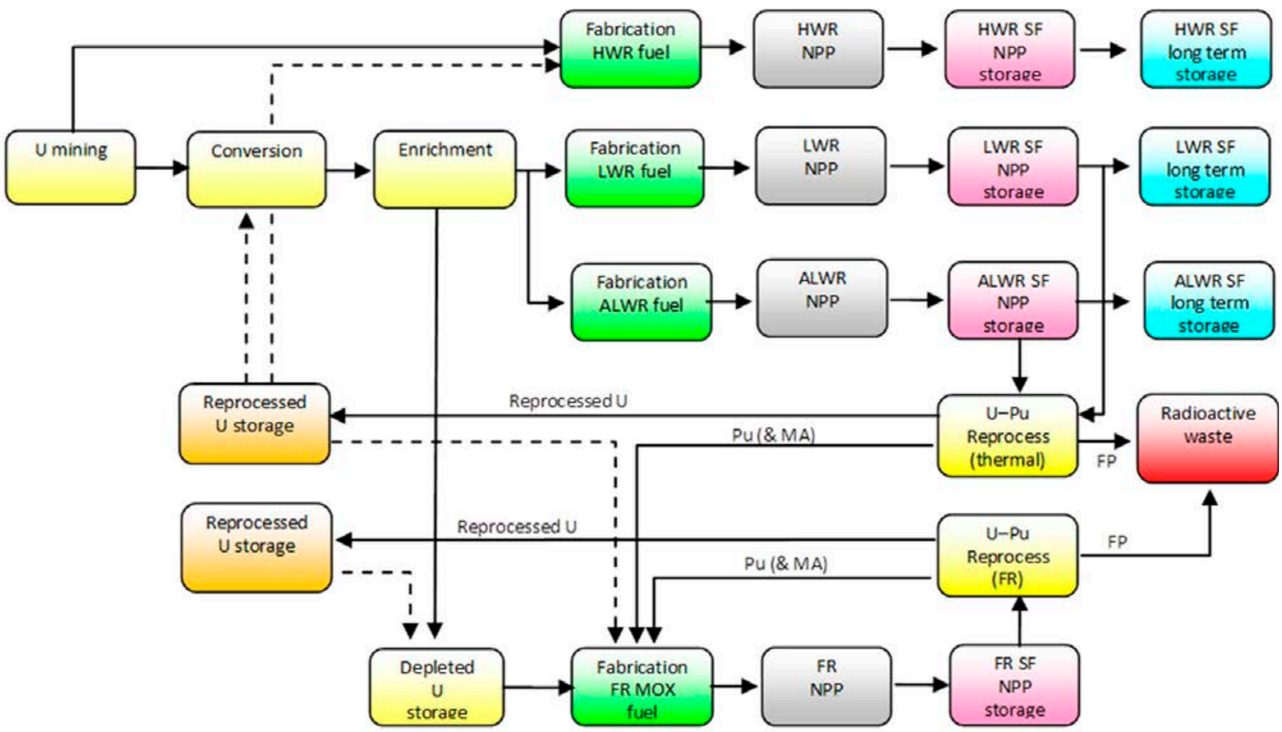

FIG. III.1. Flow chart for a combined once through cycle and fast reactor closed fuel cycle system.

III.5. INTERNATIONALLY VERIFIED DATABASE

The GAINS framework includes a collection of data (a database) for material flow analysis of nuclear energy scenarios comprising the existing and conceptual reactor designs and related nuclear fuel cycle technologies. It extends the existing IAEA databases and takes into account preferences of different countries — participants of the GAINS project. The technologies included spread from existing reactors, LWRs and HWRs, to advanced reactors, such as sodium cooled and lead cooled fast reactors of different possible designs, accelerator driven systems, thorium fuelled HWRs and minor actinide fuelled molten salt reactors. The specifications and compositions of fresh and discharged fuel for the included reactors are provided.

Three reactors types LWR, HWR and fast reactor (breeding ratio ~1.0) are considered for the BAU and BAU fast reactor framework cases. General characteristics of thermal and fast reactor (breeding ratio ~1.16) used in scenarios calculation are shown in Table III.1.

The GAINS framework incorporates several assumptions regarding the reactor and nuclear fuel cycle features. Uranium supplies are assumed to be unlimited; uranium enrichment tails assay is 0.2%. HWR share is defined at a level of 6% of the total nuclear capacity; spent fuel from HWRs is assumed to be temporarily stored. The framework also assumes there is no limitation in fuel cycle infrastructure, such as mining, conversion, enrichment, fuel fabrication, long term storage for spent fuel, interim storage for separated nuclear materials (e.g. plutonium, minor actinides and fission products), spent fuel reprocessing and geological disposal capacities. The GAINS framework imposes a constraint on the power production by fast reactors in the years 2030 and 2050s and on the total plutonium inventory in plutonium storage. The objective is to have a total generation rate of 10 GW·year from fast reactors in 2030 and a total of 400 GW·year in 2050 for the high scenario case. Plutonium inventory in

TABLE III.1. GENERAL CHARACTERISTICS OF THERMAL AND FAST REACTORS

<table>
<tr><th>Parameter</th><th>LWR</th><th>HWR</th><th colspan="3">Fast reactor (breeding ratio ~1)</th></tr>
<tr><td>Fuel type</td><td>UOX</td><td>UOX</td><td colspan="3">MOX depleted U</td></tr>
<tr><td>Electric capacity (MW)</td><td>1000</td><td>600</td><td colspan="3">870</td></tr>
<tr><td>Thermal efficiency (%)</td><td>33</td><td>30</td><td colspan="3">42</td></tr>
<tr><td>Load factor (%)</td><td>85</td><td>85</td><td colspan="3">85</td></tr>
<tr><td>Lifetime (years)</td><td>60</td><td>60</td><td colspan="3">60</td></tr>
<tr><td>Core fuel burnup (MW·d/kg)</td><td>45</td><td>7</td><td colspan="3">65.9</td></tr>
<tr><td>Construction time (years)</td><td>5</td><td>5</td><td colspan="3">5</td></tr>
<tr><td>Uranium enrichment (%)</td><td>4</td><td>0.711</td><td colspan="3">–</td></tr>
<tr><td>Cooling time (years)</td><td>5</td><td>5</td><td colspan="3">2</td></tr>
<tr><td>Reprocessing time (years)</td><td>1</td><td>1</td><td colspan="3">1</td></tr>
<tr><td></td><td></td><td></td><td>Core</td><td>Axial blanket (depleted U)</td><td>Radial blanket (depleted U)</td></tr>
<tr><td>Fuel residence time (effective full power days)</td><td>1168</td><td>292</td><td>420</td><td>420</td><td>490</td></tr>
<tr><td>Mass of the core (t HM)</td><td>78.7</td><td>83.4</td><td>12.6</td><td>5.5</td><td>6.2</td></tr>
<tr><td>Plutonium content in fresh fuel</td><td>–</td><td>–</td><td>0.22</td><td>–</td><td>–</td></tr>
</table>

plutonium storage should be kept close to zero. After 2050, there is no limitation on the capacity of fast reactors to be introduced, the deployment rate of fast reactors being then limited only by the amount of plutonium available and the overall nuclear growth rate.

III.6. KEY INDICATORS

Within the IAEA INPRO project, the sustainability assessment of a defined NES at a given moment of time is carried out using the INPRO methodology for NES assessment in the subject areas of safety, economics, environment, infrastructure, waste management, proliferation resistance and physical protection. For this purpose, the INPRO methodology defines the basic principles, the user requirements and the criteria with indicators and acceptance limits for a sustainable NES. The GAINS framework addresses scenarios of transition to sustainable NESs providing for the analysis and assessment a dynamic evolution of NESs, rather than assessment of some fixed NES at a given timeframe. In this sense, the GAINS framework is complementary to the INPRO methodology. However, owing to specific features of the material flow analysis, the GAINS metrics does not cover all of the INPRO subject areas but rather focuses on the selected issues appropriate for the problem.

To enable comparative analysis and assessment of dynamic NESs for sustainability (facilitating a judgement on whether particular transition scenarios lead to a sustainable NES), the GAINS framework provides ten key indicators with some associated evaluation parameters (see Table 2.1, in Section 2.3). This set of key indicators and evaluation parameters has been developed for the evaluations of global NES architectures and scenarios after considering more than a hundred indicators comprising all areas of evaluation of INPRO methodology. The idea is that a key indicator would have a distinctive capability for capturing the essence of a given area in application to a transition scenario, and that they would provide a means to establish targets in a specific area to be reached via improving NES composition and architecture, as well as the transition scenario. These key indicators and evaluation parameters depict nuclear power production by reactor types, resources, discharged fuel, radioactive waste, fuel cycle services, costs and investment of a global NES.

Calculation of key indicators and evaluation parameters requires appropriate material flow analysis and economic tools and methods, and such analytical methods and tools have been developed at the IAEA and in some Member States[1]:

— MESSAGE code (IAEA);
— NFCSS code (IAEA);
— DANESS code (United States of America);
— DESAE code (Belgium and Russian Federation);
— COSI code (France);
— FAMILY code (Japan);
— TEPS code (India);
— VISION code (United States of America).

In the homogeneous world model, key indicators and evaluation parameters are calculated for the whole world. In the heterogeneous world model, the key indicators and evaluation parameters could be also calculated for each group of countries (in GAINS — NG1, NG2 and NG3).

A special template was developed to facilitate the analysis of key indicators and evaluation parameters of a transition scenario under consideration. The GAINS template visualizes key indicators, evaluation parameters and mass flows and fuel cycle services for scenarios under investigation.

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability: Final Report of the INPRO Collaborative Project GAINS, IAEA Nuclear Energy Series No. NP-T-1.14, IAEA, Vienna (2013).

Appendix IV

MAJOR FINDINGS OF THE INPRO DIALOGUE FORUM ON DRIVERS AND IMPEDIMENTS FOR REGIONAL COOPERATION ON THE WAY TO SUSTAINABLE NUCLEAR ENERGY SYSTEMS

The objective of the fourth International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) Dialogue Forum, on drivers and impediments for regional cooperation on the way to sustainable nuclear energy systems (NESs) convened at IAEA headquarters, in Vienna, on 30 July–3 August 2012, was to bring together technology holders and technology users to exchange views on the benefits and issues associated with regional cooperation in building sustainable NESs and, specifically, to understand the standpoints of the user and the supplier countries with regard to the driving forces and the impediments for such a cooperation.

Multiple studies performed worldwide and, in particular, the completed IAEA study[1] on Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS), indicated that regional cooperation could secure and support a transition to sustainable NESs able to meet the diverse energy needs in the 21st century. Potential benefits of cooperation among countries are associated with:

— Minimizing infrastructure effort for national NESs of individual countries;
— Suggesting sound solutions for spent nuclear fuel utilization and disposal;
— Enabling optimum use of the available resources of all kinds;
— Minimizing costs due to the economy of scale and other factors;
— Ensuring that international commitments are met by all countries in a more easy and transparent way.

However, the feasibility of any collaborative transition to sustainable NESs depends on the balance of the driving forces and impediments all the way through such a transition. As an example, economic benefits are conventionally considered as drivers for cooperation among suppliers and users, but there are other factors that could drive or impede such cooperation. For example, considerations of security of supply might be an impediment, while the aspiration to become a technology provider may be a strong driver surpassing the least cost considerations. Similarly, resource constraints in particular countries could be a driver, while certain legal and institutional restrictions adopted on a national level may be the impediment.

A better understanding of the benefits and issues associated with regional cooperation in building sustainable NESs and a clearer vision of the driving forces and impediments behind such cooperation could help to find practical collaborative approaches based on a 'win-win' strategy for all countries involved. In particular, it could help to identify short term and medium term collaborative actions capable to develop pathways to long term sustainability.

The Forum was conducted in cooperation among the IAEA INPRO, the IAEA Division of Nuclear Fuel Cycle and Waste, the Integrated Nuclear Infrastructure Group (INIG[2]) and other IAEA Divisions and Departments. The major findings of the Forum are summarized in the following subsections.

IV.1. MOTIVATIONS AND CHALLENGES FOR COUNTRIES CONSIDERING, OR EMBARKING UPON, A NUCLEAR POWER PROGRAMME

The participants of the Forum indicated the following motivations to embark upon or expand a national nuclear power programme:

(1) Energy independence, driven by increasing concerns about the availability of fossil fuel resources at acceptable prices, as well as in anticipation of possible geopolitical tensions within and among regions around the world, when certain energy resources might become scarcer. Several countries also mentioned limitations

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability: Final Report of the INPRO Collaborative Project GAINS, IAEA Nuclear Energy Series No. NP-T-1.14, IAEA, Vienna (2013).

[2] In 2014, it was replaced by the Nuclear Infrastructure Development Section, in the IAEA Department of Nuclear Energy.

of hydropower, including both the lack of additional sites to be developed and unreliability of electricity generation due to droughts.

(2) Stability of energy prices offered by the nuclear option as opposed to the volatility of prices for fossil fuel resources. In addition, nuclear energy could be a stabilizing factor for energy parks incorporating increasingly renewable energy sources.

(3) Macroeconomic factors and strategic benefits to national economy, including:
   - Overall support to economic activities in a country, including the stabilizing effect from the consistent (non-cyclic) nature of a nuclear energy programme on the national economy;
   - Useful applications of nuclear technology (e.g. industrial and medical);
   - High scientific and technological skills associated with nuclear energy expanding the scope for multidisciplinary R&D activities in countries;
   - Potential for export of electricity to neighbouring countries.

(4) Environmental and climate change considerations, including de-carbonization of energy portfolio taking into account the limitations of other decarbonized energy resources (intermittence, capacity and applicability).

With regard to challenges facing countries wishing to embark upon or expand a national nuclear power programme and possible ways to overcome these challenges, the following was indicated by the participants of the Forum:

(1) Limitations in domestic investment capacity and financial risks, which could potentially be dealt with by nuclear power capacity sharing and co-financing.

(2) Deficiency in human resources and nuclear expertise, aggravated by growing international markets creating better job opportunities for newly trained national cadres, especially when the prestige of, and the public attitude to, the nuclear profession are relatively low in a country.

(3) Insufficient institutional and political stability, which negatively affects long term planning and licensing (this is not limited to nuclear energy alone, but applicable to all infrastructure needs spanning over the longer term). Government to government agreements especially on fuel cycle services might help in stabilizing the situation, but transparency and consistency in national energy policy is crucial over a longer time period.

(4) Public acceptance issues which could be substantially resolved by developing and embracing a comprehensive radioactive waste management strategy.

(5) Limited size of domestic electricity markets, in comparison to typical nuclear power systems. This can be compensated if regional sharing of facilities or of electricity is implemented.

(6) Limited transmission grid capacity, which impedes all electricity related activities (production and consumption). Smaller capacity generation options offered by small and medium sized reactors could reduce strains on the grid.

IV.2. CONSIDERATIONS OF COUNTRIES ALREADY HAVING A NATIONAL NUCLEAR ENERGY PROGRAMME

With regard to considerations and concerns of those countries which already have a nuclear energy programme and plan to continue its operation or to expand it, the following was indicated by the participants of the Forum in order of priority:

(1) Competitiveness:
   - The continued competitiveness of nuclear power plants, once operational, can be further improved by exchange of expertise and experience among nuclear power plant operators, either regionally or internationally (e.g. through the World Association of Nuclear Operators,WANO).
   - In some specific cases, the competitiveness of operational nuclear power plants may also be affected by the energy policies of neighbouring countries (e.g. anti-nuclear policies or oversubsidized renewable energy policies) which may impact prices and/or political influences affecting optimized operation of nuclear power plants.

— Questions also arise on ‘keeping the options open’: that is, given the regional energy policy and specifically the stance on nuclear energy, being able to keep spent nuclear fuel management options open in view of possible uncertainties with long term spent fuel and/or radioactive waste management and the ability to further optimize ultimate waste management on a regional scale.

(2) Security of supply:

— With an increasing international deployment of nuclear energy, especially the front end fuel cycle services (i.e. availability of natural uranium, conversion/enrichment and fabrication) might one day become more of a constraint impacting on the prices for these services. Specifically, smaller nuclear power plant parks might be more exposed to such influences due to their smaller leverage capacity on the international scene.

(3) Nuclear safety:

— Regional information sharing on nuclear safety and operational experiences exchange may enhance nuclear safety globally. While certain international organizations (e.g. WANO or European Nuclear Safety Regulators Group), do already exist, smaller nuclear power plant park countries may benefit from sharing certain emergency infrastructure, collaborative nuclear safety assessments of installations geared towards shared and optimized capacity building, collaboration among experts and best practices in emergency preparedness. All this could be accomplished without jeopardizing the country’s vision of independence in energy policy and organization of its nuclear safety authority and regulatory approach.

(4) Sustainability of an NES (understood in somewhat different ways by different countries):

— ‘Keeping the options open’ ranging from once through fuel cycles to advanced Generation IV type NESs is seen as important in view of leveraging the exposure to possible consequences of an internationally rapid growth of nuclear power deployment. Some countries do have the capability to embark upon more advanced fuel cycle options, while others still lack the scale of a nuclear power park or are politically constrained to use the existing commercial back end spent nuclear fuel management options. Use of the existing commercial back end fuel cycle services may, however, be the first step towards more sustainable NESs.

— Especially with respect to ultimate waste disposal, and in the context of deciding on spent nuclear fuel being part of this ultimate waste, many Member States are looking for a stable regional and even international framework to make decisions.

(5) Proliferation resistance:

— Regional collaborations, such as the European Atomic Energy Community (Euratom), the Brazilian–Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), as well as international collaborations such as the World Institute of Nuclear Security, already exist and may provide avenues for other regions to ensure continuous trust between Member States, in addition to IAEA international safeguards, facilitating deployment of nuclear energy.

(6) Spent nuclear fuel management and ultimate waste disposal, including concerns on differing policies of countries across a region:

— Economies of scale apply in spent nuclear fuel management and, even more so, in ultimate waste disposal. In spent nuclear fuel management, regional interim storage solutions or at least coherent approaches across countries having smaller nuclear power plant parks may be beneficial. For geological waste disposal, the principal question is whether it is possible to consider regional disposal facilities benefiting from economies of scale, given the large fixed cost of such facilities. Other benefits of regional disposal facilities are related to design and licensing costs.

(7) Energy independence was also confirmed as an important consideration for countries that already have NESs and are planning to expand the use of peaceful nuclear energy.

IV.3. DOMAINS FOR REGIONAL COLLABORATION

The domains for potential regional collaboration among countries were indicated as follows:

(1) Regional (nuclear) energy planning, which would help to optimize the investments in regional markets and contribute to enhanced energy independence, reduction of greenhouse gases emissions, and price stability.

New business models may develop where energy intensive industries would define the regional/local energy policy.

(2) Education and training, including undergraduate and graduate education and training for technicians, as well as continuous professional development. Collaboration may include coordinated university curricula as well as ‘pooling’ of the professors. Examples of such collaboration already exist (e.g. European Nuclear Education Network, World Nuclear University, Ghana–Egypt bilateral cooperation programmes in nuclear education). Cooperation in nuclear education and training may also cover ‘training of trainers’ and student exchange programmes (e.g. PhDs and internships). For all of the above potential collaborations, utility or sector specific regional training platforms could be created.

(3) Human resources and expertise, including creation of shared service and operation companies for nuclear power plants, creation of shared emergency intervention companies and creation of provisions for the support of centralized operation and maintenance and fuel cycle services (e.g. enrichment, reprocessing, interim storage and ultimate waste geological disposal facilities). Sharing may also consider regulatory bodies’ R&D support organizations; however, considerations of each country’s sovereignty would prevent sharing of the fundamental national regulatory functions, such as licensing. Collaboration on human resources and expertise may also help to overcome ‘scale’ factors (i.e. smaller utilities may share otherwise scarce resources on safety). One example could be the Electric Power Research Institute, in the United States of America.

(4) R&D, where collaboration may include regional R&D infrastructure platforms and centres of excellence. It may also include international R&D programmes (e.g. within INPRO) and other projects, such as the Generation IV International Forum. Benefits may also come from better use of results of existing R&D (‘a month in the library can save a year in the lab’).

(5) Waste management, where collaboration can be valuable in waste minimization procedures, characterization, treatment, storage and disposal. A key focus could be on shared development of ultimate geological waste repository and optimization of repository capacity.

(6) Decommissioning, where collaboration could focus on assurance of expertise, methods and capacity over longer time periods.

(7) Proliferation resistance and international safeguards, wherein regional organizations could be created to examine the development of safeguards methods and techniques, discuss safeguards implementation issues and conduct joint training sessions in full compliance with IAEA international safeguards protocols. The existing examples are Euratom and ABACC, which both assured a continuous trust among the involved Member States.

IV.4. WHAT IS A SUSTAINABLE NUCLEAR ENERGY SYSTEM?

With regard to sustainability of NESs, different visions were expressed by different participants. Several participants named all areas rated important for sustainability by the INPRO project (i.e. economics, waste management, environment, proliferation resistance, physical protection, safety and infrastructure). Others mentioned only several of the above mentioned areas. For countries considering development of a nuclear power programme, sustainability issues tended to focus on public acceptance, financing and general economics and assurance of fuel supply.

For countries which already have larger NESs, the issue of initiating and delivering services internationally to jointly improve the global and national sustainability was noted. Here, the development of both advanced nuclear power plants and R&D on the nuclear fuel cycle was rated important. The priorities for sustainability of NESs were identified as follows:

(1) Safe and secure nuclear facilities;
(2) Secure supply of front end fuel cycle services;
(3) Secure supply of back end fuel cycle services, including spent nuclear fuel reprocessing;
(4) Access to geological disposal facilities.

IV.5. SYNERGIES ON THE WAY TO SUSTAINABLE NUCLEAR ENERGY SYSTEMS

Synergistic approaches that would combine various NES options deployed within different countries into a globally, more sustainable NES were discussed, although without fully detailing how to move into that direction. All participants embraced the idea that such synergistic development would or could be beneficial, though the drivers towards such development should primarily be induced by the current nuclear technology leaders (China, France, India, Japan, Republic of Korea, Russian Federation and United States of America).

Synergies among technological options related to nuclear power plant types and their fuel cycles (e.g. reprocessing and recycling of spent nuclear fuel, such as mixed oxide, DUPIC, partitioning and transmutation) as well as collaboration policies of the technology suppliers and users and newcomer countries could be of benefit for transitioning to sustainable NESs. However, collaborations would be viable only if based on a ‘win-win’ strategy for both suppliers and users (‘by sharing, we win together’). The ‘not-invented-here syndrome’ from some technology holder or aspiring technology holder countries may hamper collaboration.

IV.6. DRIVERS FOR REGIONAL COOPERATION ON THE WAY TO SUSTAINABLE NUCLEAR ENERGY SYSTEMS

Participants of the Forum specified the following drivers for regional collaboration to support transitioning to sustainable NESs — listed without priority:

(1) Drivers related to energy policy:
- Those include the possibility to enhance energy security through assuring energy independence on a regional level. Collaborative actions could include providing interconnectivity of transmission grids and optimization of regional generating capacity portfolios.

(2) Economic and macroeconomic factors:
- Those include various possible benefits measured in cost savings and mitigation of the investment risks. Investment risks could be mitigated by rendering investment at a level feasible for smaller scaled utilities and investors as well as by assuring a more stable energy market for baseload nuclear generation.

(3) The possibility of shared resource management, including:
- Regional collaboration in R&D (e.g. Euratom) as well as collaborations in radioprotection, waste management and pre-regulatory R&D, among others.
- Expertise sharing on licensing, regulations, radioprotection and environmental impact assessments.
- Specialized human resource and expertise sharing in accident management and environmental remediation, pre-regulatory R&D, scientific and technical support of nuclear power plant operation, education and training (e.g. regional networks of nuclear education programmes), and knowledge transfer across generations of experts.
- Specialized R&D infrastructure, with a potential to create regional centres of excellence within a global nuclear R&D scene.

(4) Security of supply considerations, including;
- Assurance of fuel supply (i.e. assurance of nuclear power plant operation), which could be achieved by co-investment in, or joint development of, natural uranium resources, creation of an international or regional nuclear fuel bank and by multiplicity of suppliers or by long term contracts. Access to three or more suppliers of any material or service was preferable versus single supplier arrangements.
- Effective spent fuel management, including longer term interim fuel storage (e.g. on regional interim storage sites) or reprocessing and recycling with regional optimization of recycling schemes according to regional nuclear power plant park specifics (optimization of cross-flows and recycle of fissile materials along nuclear power plant types and parks present in the region, e.g. use of reprocessed uranium in CANDU reactors).

(5) Ultimate waste management considerations, including an option of optimizing geological repository costs, through adopting a holistic view of the global NES. Cooperation among, or consolidation of, organizations dealing with waste could be a promising direction.

(6) Considerations of best practice sharing, including safety (e.g. Western European Nuclear Regulators Association), operational performance (e.g. WANO), and science and technology (e.g. IAEA).
(7) Considerations of risk management, including several models for shared nuclear power plant development with the vendor, such as build–own–operate (transfer), which will transfer risk to the vendor who may have more experience or larger financial assets. In this case, liabilities under international legal instruments could still be an issue.

IV.7. IMPEDIMENTS FOR REGIONAL COOPERATION ON THE WAY TO SUSTAINABLE NUCLEAR ENERGY SYSTEMS

Participants of the Forum specified the following impediments for regional collaboration in order of priority:

(1) National regulations which still have essentially a national focus and sometimes prohibit synergistic collaborations with other countries.
(2) National laws that often prohibit accepting third parties' ultimate waste for storage and final disposal. Overcoming this impediment would require harmonization of ultimate waste conditioning characteristics (e.g. vitrified waste) to optimize shared use of repository.
(3) 'Wait and hope for Generation IV' considerations which could be expressed as 'why invest in new Generation III products, if Generation IV would provide better solutions in a number of years'?
(4) Considerations of sovereignty.
(5) Protective policies that reject solutions that are 'not invented here', with indigenous technology development and mastering seen as a competitive advantage.

Non-uniform sociopolitical stance on nuclear energy wherein dislike of nuclear power by the neighbouring Member States may impact deployment capacity in a given Member State.

IV.8. PREREQUISITES FOR REGIONAL COLLABORATION

IV.8.1. Sociopolitical environment

Participants of the Forum indicated public acceptance of nuclear energy and political and institutional stability are necessary to enable regional collaboration in support of transitioning to sustainable NES.

IV.8.2. Factors limiting collaboration in the nuclear area compared to other energy areas

Participants of the Forum identified the following major factors that restrict regional collaboration in the nuclear area:

(1) The long term nature of nuclear energy projects, spanning more than 100 years (including construction and decommissioning periods), which naturally raises concerns regarding commitment for very long term cooperation with other countries;
(2) The strategic nature of nuclear energy in view of energy independence and nuclear technology development, which may raise concerns regarding possible negative impacts of cooperation on national strategic goals;
(3) Concerns related to nuclear proliferation;
(4) Nuclear energy essentially remains an energy source requiring government policy and is not in the hands of industry only.

IV.8.3. Factors favorable for regional cooperation

Participants of the Forum identified the following major factors that would support long term regional collaboration for sustainable NESs:

(1) Long term international policy regarding sustainability of NESs.
(2) International governance of drivers for transitioning to sustainable NESs, potentially impacting local decisions on nuclear power plant types or fuel cycle options to benefit global nuclear energy sustainability. Some participants suggested this might require the implementation of some analogue to the carbon tax/green certificate system. The criteria could be tonnage of ultimate waste produced per TW(e) or contribution to a global conversion ratio as a measure for resource sustainability.
(3) Establishment or regional nuclear fuel cycle centres, including storage and disposal.

IV.8.4. Market developments which could facilitate a collaborative transition to sustainable nuclear energy systems

Participants of the Forum identified the following market developments that could facilitate regional cooperation towards building sustainable NESs:

(1) New business models for newcomers, including 'full service' contracts (licensing, construction, safeguards and nuclear fuel cycle) with local and regional financing. Some participants mentioned those could be linked to establishment of small and medium sized reactor markets.
(2) Fuel leasing, which implies that the leasing country would take back the spent fuel and dispose of any wastes arising from this fuel on its own territory or in an international facility in a third party country.
(3) Business models that provide assurance of operational performance, including assurance of operation and maintenance, assurance of fuel supply, assurance of spent fuel management and assurance of best practice waste management. However, the policy for ultimate waste management remains a national government decision.

IV.9. OPEN QUESTIONS

Participants of the Forum identified the following open questions regarding regional cooperation towards building sustainable NESs:

(1) The role of governments versus markets and, in particular, what are the drivers for government decisions towards more collaboration? Here, the important specific considerations are:
    — Commercial or multi-governmental regional arrangements could be more stable that arrangements of individual governments.
    — Regional collaboration could contribute to global safety and security by leading to fewer sensitive nuclear facilities.
    — However, there are concerns that profit driven companies having experience with other (non-nuclear) energy sources may not have the safety culture required for NESs.
    — Grid operators need to be aware of the unique characteristics of nuclear systems.
    — Responsibility for developing national infrastructure for nuclear power rests with the governments, while private entities do not have this as their main responsibility.
    — Governments may consider initiating cooperative agreements (e.g. for establishing a multi-government entity) and charging it with the responsibility of regional energy management. The multi-government entity could then contract with industry while maintaining the responsibility to report to the governments and therefore the population.
    — It is not clear how the objectives of shared expertise building and achieving regional leadership (e.g. through higher economic competitiveness) go together.
    — Standpoints of countries on energy security vary from achieving full independence and indigenous capacity to increased energy portfolio diversification and international cooperation.
(2) Could industry take the risks towards development of sustainable NESs alone (the market is always seeking new business models and solutions when there is a demand)?

Appendix V

OPTIONS FOR ENHANCED NUCLEAR ENERGY SUSTAINABILITY

In 1987, the Brundtland Commission [V.1] defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. The Brundtland Commission influenced the development in 1992 of Agenda 21 by the United Nations [V.2], which provided a blueprint for achieving development in the 21st century that is socially, environmentally and economically sustainable.

Energy was recognized as a key component of sustainable development. Considerations of sustainability should therefore play an essential role in defining energy policy priorities of technology user and technology holder countries alike. The Commission on Sustainable Development, in conjunction with several other organizations, produced a set of indicators (metrics) for sustainable energy development [V.3]. These indicators can be grouped into economic, environment, social and institutional areas.

Recognizing that nuclear energy would be an important contributor to global energy sustainability, the IAEA established in 2000 the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) with one of the main objectives to help to ensure that nuclear energy is available to contribute in fulfilling, in a sustainable manner, energy needs in the 21st century.

One of the first activities of INPRO was to develop a method for assessing the sustainability of a nuclear energy system (NES). The INPRO methodology [V.4–V.7] is a nine volume report, currently undergoing a revision process with two new volumes already published, which explains how to evaluate NES sustainability in the areas of economics, infrastructure, waste management, proliferation resistance, environment and safety of nuclear installations.

An NES that meets all of the acceptance limits in the INPRO methodology is deemed to be sustainable. However, sustainability beyond the requirements of the acceptance limits may be achieved [V.4–V.6]. This publication presents discrete options for enhanced NES sustainability based on use of advanced fuel cycles[1]. The generic options for enhanced nuclear energy sustainability are in two directions:

— Enhancing sustainability via advanced reactors and fuel cycles;
— Collaborative enhancements.

V.1. ENHANCING SUSTAINABILITY VIA ADVANCED REACTORS AND FUEL CYCLES

The UN concept of sustainable development includes economic, environmental, social and institutional dimensions. When mapped against these dimensions, the unique characteristics of nuclear energy result in seven specific subject areas in the INPRO methodology: economics, infrastructure, waste management, proliferation resistance, physical protection, environment and safety of nuclear installations.

Enhanced sustainability in one or more of these subject areas may be achieved through improvements in technologies and/or changes in policies, as well as through enhanced cooperation among countries, including the technology holder and technology user countries[2] and internationally recognized bodies responsible for defining sustainable energy policy on a global scale. This publication identifies several specific options for enhanced sustainability achievable through the application of advanced technologies in reactors and related nuclear fuel cycles. This set of options is proposed as a basis of the Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems (ROADMAPS) collaborative project and future development of INPRO Task 1: Global Scenarios).

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[1] Advanced fuel cycles in their front end may generically include identification of additional resources and development of improved mining techniques.

[2] The division into technology holders and technology users is not static, the situation is actually evolving.

The options are organized based on the following principles:

— Structured along generic fuel cycle options, with generic reactor options linked to fuel cycle options. The reason for this is that the generic reactor technologies may be common for several generic fuel cycle options, while the generic fuel cycle options are limited in number and well known.
— While the diverse set of generic options is presented, stating preferences or subjectively ‘picking winners and losers’ is avoided.
— The diversity of options is presented in the broad sense inclusive of all Member States’ positions.

All options are treated equally, in a neutral, balanced and objective manner.

V.2. OPTIONS FOR ENHANCED SUSTAINABILITY

V.2.1. Option A. Once through nuclear fuel cycle

This is currently the most widespread, although not the only option realized in the majority of countries using nuclear energy. The reactors currently operated in a once through fuel cycle include multiple light water reactors (LWRs) including those with a graphite moderator, gas cooled reactors, heavy water reactors (HWRs) and also some additional reactor types. By the end of the decade, one nuclear power plant with two indirect cycle high temperature gas cooled reactors intended for electricity generation only will join the family. Within the next decade, advanced LWRs may be put in operation, and within several decades from the present some systems being developed by the Generation IV International Forum, for example very high temperature reactors (VHTRs) or supercritical water cooled reactors (SCWRs), might be deployed.[3] One lead–bismuth cooled fast reactor design is under development and is being designed to operate in a variety of nuclear fuel cycles, including the once through fuel cycle. A prototype might be deployed within the coming decade.

The once through fuel cycle does not require proliferation sensitive chemical reprocessing technologies, but in most cases (with the exception of the majority of HWRs) it requires proliferation sensitive fuel enrichment technology. With a few enrichment service vendors providing services on a global scale under bilateral or multilateral agreements among countries, open market conditions are emulated with respect to enrichment services worldwide. Considerations of security of supply are also important for some countries, and those are addressed through the IAEA fuel bank in Kazakhstan and the International Uranium Enrichment Center, in Angarsk, Russian Federation.

The once though fuel cycle makes it possible to utilize only a small fraction (<1%) of natural uranium, and in this sense it is most sensitive to natural uranium resource availability. At present, the consensus is that globally available natural uranium resources would be sufficient for global nuclear energy operation with Option A for the next 50 years, taking into account the projected global capacity growth rate [V.7].

The once through fuel cycle also results in the production of a direct use material — reactor grade plutonium [V.8][4] — which is present in the spent nuclear fuel, first, in irradiated form, and in several hundred years, probably, in unirradiated form[5] which suggests that safeguards and security measures [V.9] will be applied to spent fuel in perpetuity.

Some innovative reactor design concepts being considered for operation in a once through nuclear fuel cycle offer significant improvements in fuel utilization, comparable or even exceeding those attained in the limited recycling option (Option C); among them are VHTRs with deep burn fuel and breed and burn reactor concepts. Most of them still require substantial RD&D to be deployed. Most, if not all, of the above mentioned reactors are also being considered (or could be considered) for operation in a closed nuclear fuel cycle (Options B–E, see

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[3] Several sodium cooled fast reactors (SFRs) in operation currently are using once through fuel cycle within technology demonstration programmes; however, the final goal of all SFRs is to operate in a closed nuclear fuel cycle.

[4] Fresh and spent mixed oxide fuel and spent uranium oxide nuclear fuel containing reactor grade plutonium are specifically mentioned in the definition of direct use material. Unirradiated direct use material requires the most stringent safeguards measures.

[5] Irradiated and unirradiated relate to material category technical designations determined by the IAEA for the purpose of determining safeguards approaches and measures. Irradiated implies the presence of ‘substantial amounts’ of radioactive fission products. After several hundred years of decay, the dose of fission products in spent nuclear fuel is expected to be sufficiently low as to render the material ‘unirradiated’.

below). One design concept of the advanced HWR making use of the thorium–uranium based heterogeneous fuel assemblies is under confirmatory R&D. The uranium savings in this concept are ensured through the production of more than a half of the thermal energy from fission on ^{233}U bred and burned in situ from thorium.

Option A, as well as recycle Options B–E, include the disposal of low level and intermediate level waste. Like all other fuel cycle options, Option A (once through nuclear fuel cycle) will not be sustainable without final geological disposal of high level waste (HLW), which in this case would be direct spent nuclear fuel disposal (see Option F below).

V.2.2. Option B. Recycle of spent fuel with only physical processing

This option provides for a single recycle of used nuclear fuel from reactors of a particular type in nuclear reactors of another type, with no chemical reprocessing applied. It could to a limited extent help to save natural uranium resources and to reduce spent nuclear fuel volume for final disposal, while avoiding the use of proliferation sensitive chemical reprocessing technology. Fuel enrichment will, however, be required.

The concluded R&D on this technology in application to LWR spent nuclear fuel single recycle in HWR — the direct use of spent PWR fuel in CANDU reactors (DUPIC) process — are deemed sufficient for practical implementation. However, this had not taken place so far, since with current uranium prices, this option is more expensive than Option A. Other reactor options might perhaps be considered. Like Option A, Option B (recycle of spent fuel with only physical processing) cannot be considered as sustainable without final spent nuclear fuel disposal (see Option F below). Moreover, spent fuel in Option B also has similar safeguards and security characteristics as spent fuel in Option A in storage and in geological disposal.

V.2.3. Option C. Limited recycling of spent fuel

This enhancement option is a step in improving resource utilization and reducing the waste burden. Limited recycling reduces spent nuclear fuel volumes, slightly improves resource utilization and keeps fertile fuel resources more accessible for later options of sustainability enhancement, thus offering some flexibility for long term management of nuclear materials. The achieved effects are similar in magnitude, albeit somewhat larger than in Option B described above.

This option requires the development and deployment of the proliferation sensitive commercial spent fuel (chemical) reprocessing and the fabrication of fuel from previously irradiated materials. Some Member States have already deployed these technologies and are successfully operating them on a commercial scale for several decades, providing spent nuclear fuel take back services with the return of ‘ultimate’ waste — vitrified mixture of fission products and minor actinides and LWR mixed oxide fuel and fuel from reprocessed uranium supply services to a number of other countries. This ongoing experience illustrates the option to avoid broad dissemination of the proliferation sensitive chemical reprocessing technologies by concentrating the production on a limited number of sites that could provide recycling services to multiple customers abroad.

The reactors (potentially) operating under this option include LWRs, HWRs, VHTRs and SCWRs, among others. In practice, most fuel cycles at this option will involve limited recycle in a ‘twice through’ system (recycling nuclear material once, then keeping irradiated recycled fuels in interim storage), although other options are possible, including closed fuel cycles that are not fissile material self-sufficient and require external support of fissile material inventory, which has already been demonstrated on a large scale.

Like Options A and B described above, Option C requires the use of proliferation sensitive enrichment technologies, while it also uses proliferation sensitive chemical reprocessing technologies. Final disposal of both HLW and spent nuclear fuel is required to consider sustainability for this fuel cycle option (see Option F). It could also be noted that no country has stated that Option C (limited recycling of spent fuel) would be their final fuel cycle option, but instead countries consider it as a transition from Option A to Option D (complete recycle of spent fuel).

Storage and disposal of spent nuclear fuel would have similar safeguards and security characteristics as in Option A. HLW, on the other hand may significantly reduce safeguards requirements if the IAEA determines that it is a waste with characteristics that allow termination of safeguards (see paras 11 and 35 of Ref. [V.10]). At the same time, large scale spent nuclear fuel reprocessing, plutonium storages and handling and plutonium fuel fabrication, all imply the most stringent safeguards and security measures on bulk and item material inventories that do not exist under Options A and B. With this, it should be noted that a practical example of safeguards implementation for industrial scale spent nuclear fuel reprocessing exists.

V.2.4. Option D. Complete recycle of spent fuel

With the use of a closed fuel cycle and breeding of fissile material, all natural resources of fissile (^{235}U) and fertile (^{238}U) uranium and thorium (^{232}Th) could eventually be utilized through the conversion of all fertile nuclear materials into fissile with their subsequent fission. This option realizes nearly[6] full utilization of the energy potential in nuclear fuel. This enhancement option also reduces the long lived radiotoxicity burden of HLW by up to an order of magnitude by keeping plutonium out of the waste.

If Option D is fully implemented, the use of previously mined uranium currently in used nuclear fuel and depleted uranium stocks solves the fuel resource utilization issue by providing fuel indefinitely (>1000 years) without any additional uranium mining.[7] This enhancement also helps to achieve the Brundtland Commission objectives for utilization of non-renewable resources. While the current generation will use some amount of current resources, they also will enable future generations to extract more energy from the remaining resources than was used by all previous generations combined.

This option requires the development and deployment of breeder or break-even (breeding ratio ~1) reactor technology, but reduces or eliminates the need for proliferation sensitive uranium enrichment. The option may be based on either uranium or thorium as a source of fertile materials, including materials from LWR spent fuel. However, this option can only be achieved in the very long term as its deployment will — in many strategies — be constrained by the availability of plutonium or ^{233}U from spent nuclear fuel and may require a large share of fast reactors (up to 60% or more of the total nuclear fleet). Notwithstanding this, to become a reality in the future, the technology needs to be developed at present.

Like Option C, Option D (complete recycle of spent fuel) could avoid broad dissemination of the proliferation sensitive wet or dry chemical reprocessing technologies by concentrating the production on a limited number of sites that could provide recycling services to multiple customers abroad not having the chemical reprocessing plants domestically, under the international nuclear trade framework, as discussed in Section V.4.

The reactors that could operate under this option include, but are not limited to, any breeder or break-even reactor and burner reactors that use excess fissile material from the breeder reactors. Therefore, they could include LWRs, HWRs, SFRs, lead cooled fast reactors (LFRs), gas cooled fast reactors (GFRs), VHTRs and molten salt reactors (MSRs). Of the fast reactors, one SFR has started its operation in a demonstration mode[8], and another one in the commercial electricity generation mode, while LFR and GFR projects are under development at different design stages in several countries. Possible deployment dates for LFR are several decades from the present. One LFR design being developed currently is targeted for deployment by 2030. For MSRs, the developments are at early design stages and their deployment is not envisaged before the mid century.

To become sustainable, Option D (complete recycle of spent fuel) would also need to be coupled with Option F. Different from Options A–C, in Option D, disposed material would be HLW composed of fission products and minor actinides.

As under Option C, large scale spent nuclear fuel reprocessing, plutonium storages and handling and plutonium fuel fabrication, all imply the most stringent safeguards and security measures on bulk and item material inventories that do not exist under Options A and B. A practical example of safeguards implementation for industrial scale spent nuclear fuel reprocessing exists.

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[6] Neptunium-237, a minor actinide, contains roughly 5% of the plutonium energy in thermal reactor spent fuel, with production increasing with burnup. In Option D, where only uranium, plutonium and thorium are assumed to be recycled, this results in a limited but substantive loss. Compared to other minor actinides, neptunium appears to be easily recyclable in fast reactor cores. Therefore, some countries may consider nearer term options on neptunium co-extraction and recycle with uranium and plutonium; in this case, the utilization of the energy potential in nuclear fuel would become practically complete.

[7] The issue of natural resource depletion is, however, not limited to uranium or thorium (fuel source materials) and is faced by most technologies including renewables. All require a large set of mineral resources that underlie manufacturing materials. Some of these minerals are much rarer than others.

[8] There are also a few experimental SFRs operating or being prepared for operation.

V.2.5. Option E. Minor actinide or minor actinides and fission products transmutation

A closed fuel cycle recycling all actinides and only disposing fission products would provide the maximum benefits for combined resource utilization and waste hazard minimization. This enhancement option builds on the technologies of the previous options, but also requires the development and deployment of minor actinide reprocessing/partitioning, minor actinide bearing fuels/targets, and remote fuel/target fabrication technologies.

A couple of decades ago, an option to transmute, along with minor actinides, also long lived fission products was considered. As it was found that long term radiotoxicity of long lived fission products is much less than that of the minor actinides, further research along this trend faded.

The nuclear installations that could be used under Option E (minor actinide or minor actinides and fission products transmutation) include fast reactors, accelerator driven systems (ADSs) and MSRs. While a substantial progress with RD&D on ADSs is noted in some Member States, the realistic deployment dates for such facilities are in the second half of the present century. According to detailed studies performed in some countries, it is expedient to start transmutation in dedicated blanket zones of fast reactors, not to jeopardize the reactor safety. More radical approaches to transmutation (e.g. in fast reactor cores or in high minor actinide content ADS blankets) could then be pursued gradually, within a minimum investment risk strategy.

Final disposal of HLW, which under this option could be mostly fission products, is required to consider sustainability of Option E. As the primary difference between Options D and E is to reduce the long term waste hazard, when compared to Option D, Option E might provide limited benefits at potentially higher cost, depending on the geology of the HLW repository.

As under Options C and D, large scale spent nuclear fuel reprocessing, plutonium storages and handling and plutonium fuel fabrication, all imply the most stringent safeguards and security measures on bulk and item material inventories that do not exist under Options A and B. A practical example of safeguards implementation for industrial scale spent nuclear fuel reprocessing exists.

Different from Options C and D, some reprocessing and processing technologies that may be employed in Option E may involve separation (from fission products) of neptunium and americium. Neptunium and americium are sometimes referred to as alternative nuclear materials (ANMs), which may require special treatment under IAEA safeguards [V.8][9]. In the event that large amounts of ANM are to be separated from fission products, the IAEA will have to make a determination about how to proceed in this case. Currently, there is a solution applied under specific voluntary arrangements with the Member States where this is applicable. An approach called ‘flow sheet verification’ is used in PUREX to demonstrate that ANM remains together with fission products. Currently, there are no general approaches developed for cases in which large quantities of ANM are separated from fission products — such approaches may require development.

V.2.6. Option F. Final geological disposal of all wastes

Option F (final geological disposal of all wastes) — spent nuclear fuel and HLW — applies to Options A–E. In this context, each generic fuel cycle option can be amended by adding Option F (e.g. AF, BF, CF, etc.) and only with such amendment could they be considered sustainable. The disposal material would however be different for different options. For Options A–C, it would be spent nuclear fuel (plus HLW for Option C), while for Options D and E it would only be HLW. For Option D, this would be a mixture of fission products and minor actinides; for Option E, a combination of fission products, potentially, without all or some long lived fission products and minor actinides.

While current NES include provision for future disposal of all wastes, and several final repository projects are under way, no current NES has opened disposal facilities for spent nuclear fuel or HLW. Option F addresses the political issue of waste management through the disposal of spent nuclear fuel and HLW. Retrievability of spent nuclear fuel and HLW may be required to not limit options for future generations, who may wish to use the spent nuclear fuel as a fuel resource or to implement improved HLW management options.

Direct spent nuclear fuel disposal (Option A) may have additional long term safeguards and security implications. For example, with respect to the disposal facilities in the ongoing repository projects, prior to the

[9] See definitions in 4.18. Americium and 4.19. Neptunium in Ref. [V.8]. Neptunium, in particular, has comparable fast fission, heat and radiation properties as ^{235}U.

facility closure there will be a 100 year, open operation period with the safeguards approach for this period already defined. However, according to provisions of comprehensive safeguards agreements, safeguards on nuclear material can only be terminated if it is determined to be unrecoverable, but that may not be the case after closure of the facilities. Therefore, there would be 100 years to figure out exactly how to apply safeguards for the very long term. Currently, there is no agreement on how to proceed in the long term, but concepts are being studied.

Under Options C–E, where large scale spent nuclear fuel reprocessing, plutonium storages and handling and plutonium fuel fabrication will be required, the most stringent safeguards and security measures on bulk and item material inventories that do not exist under Options A and B would need to be implemented. However, as it was already mentioned, a practical example of safeguards implementation for industrial scale spent nuclear fuel reprocessing exists.

Although HLW packages stored or disposed in Options D and E may be determined by the IAEA as qualified for termination of safeguards, in some plausible scenarios pertaining to these options considerable spent nuclear fuel may remain in storage and some may be disposed in geological repository. This spent nuclear fuel has similar safeguards and security characteristics as under Option A.

It should be noted that higher operating temperature reactors and potential process waste heat utilization (non-electrical applications) may on their own have the effect of extending the fuel resource base and reducing spent nuclear fuel accumulation. For the same energy consumption by customers, they will result in lower specific uranium consumption and spent nuclear fuel accumulation, compared to lower temperature reactors and the reactors without non-electrical applications. Non-electrical applications generically fit to all reactor technologies; however, applications will depend on a temperature range and scale. They have some positive commercial experience of the past, but limited progress is observed currently

Higher reactor temperatures and the resulting higher nuclear power plant efficiencies are characteristic not only of dedicated high temperature reactors or VHTRs, they are also typical of SFRs, LFRs, GFRs, MSRs and SCWRs.

Finally, small and medium sized reactors and small modular reactors may significantly expand nuclear energy markets by bringing nuclear to where large nuclear power plants do not fit (e.g. areas with sparse population and lower energy demand, remote areas and islands, regions with small electricity grids, and infrastructure of decommissioned small sized coal power plants, among other things). By expanding nuclear markets, these types of reactor could enhance the contribution of nuclear energy to sustainable development of economies in many countries and also to greenhouse gas emission reductions. They are being developed within a variety of reactor technologies, including most of the ones mentioned above, as well as for a variety of fuel cycle options. With several projects already in the deployment stage, their progress will depend on the ability of their manufacturers to substitute the economy of scale by the economy of mass production of serial modules. The next two decades are likely to demonstrate whether this can be achieved.

Sustainability Option A (once through nuclear fuel cycle) is fundamental to any sustainable NES. Options B (recycle of spent fuel with only physical processing), C (limited recycling of spent fuel), D (complete recycle of spent fuel) and E (minor actinide or minor actinides and fission products transmutation) can progressively improve resource sustainability of an NES while also reducing the long term waste burden. This may in turn facilitate the achievement of Option F (final geological disposal of all wastes). However, care needs to be taken that the advanced technologies and infrastructure deployed do not significantly increase overall costs. Competitive economics versus other energy options is, and would remain, an important driver for nuclear energy development, along with national and international considerations such as diversification of resources or environmental objectives such as greenhouse gas emission reduction. It could also be noted that moving from Option AF to Option EF may be a dynamic process involving multiple countries and partnerships.

In the above mentioned classification, Option A (once through nuclear fuel cycle) represents technologies commercially available today (thermal reactors, wet and dry storages of spent nuclear fuel). Some Option C (limited recycling of spent fuel) technologies are also commercially available today in a limited number of technology holder countries. For the other options, R&D is in progress in a number of countries, including under international collaborations such as the Generation IV International Forum, including the European Sustainable Nuclear Industrial Initiative.

V.3. COLLABORATIVE ENHANCEMENTS

One of the effective solutions to bring the benefits of enhanced sustainability options to a broader variety of users is through cooperation between countries in fuel cycle operations. This has been shown in previous INPRO studies [V.11] to reduce the technology development and infrastructure needs of newcomers and countries with smaller nuclear energy programs, while assisting other cooperating countries in acquiring the benefits of enhanced sustainability options. The infrastructure basic principle in the INPRO methodology includes the development and provision of regional and international arrangements. Analysis of benefits of cooperation in the nuclear fuel cycle was one of the objectives of the INPRO Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES) collaborative project. The project looked for options to amplify the benefits of innovation through synergistic cooperation in nuclear fuel cycles.

To present options for collaborative enhancement, this appendix presents a summary description of the present status/specifics of nuclear trade, including bilateral and multiple bilateral agreements, and multilateral agreements. The core issue to be addressed is whether and how to achieve competitive market conditions within a given nuclear trade regime.

All seven of the sustainability subject areas in the INPRO methodology can be enhanced through collaboration. Safety is improved through the exchange of not only advanced technology, but also information and knowledge on safety requirements and design certification, as well as human resources. Proliferation resistance and nuclear security can be improved by limiting the number of sites that employ enrichment and reprocessing technologies and associated fissile material stocks. Economics and infrastructure are improved through judicious investments in R&D and improved learning and economies of scale of larger fuel cycle infrastructures. Security of supply could be improved via political arrangements. Finally, the environment and waste management areas are improved by enabling more countries to achieve the benefits of enhanced NES sustainability options, for example through the use of fuel cycle services provided by countries with recycling capabilities or through eventual multilateral solutions for waste repository.

It is important to note that nuclear trade and cooperation is substantively different from trade and cooperation in many other fields in that it is more stringently regulated (i.e. governed by the agreements between countries and between countries and the IAEA). These ‘agreements for peaceful nuclear cooperation’ have more complex terms, restrictions and obligations than found under agreements governing trade of general commodities, goods and services. The current status of international trade and cooperation on nuclear power and nuclear fuel cycles is summarized in the following section.

V.4. INTERNATIONAL TRADE AND COOPERATION ON NUCLEAR POWER AND FUEL CYCLE

The current nuclear trade regime is governed predominantly under bilateral agreements for peaceful nuclear cooperation (hereafter referred to as ‘bilateral agreements’). These agreements are typically umbrellas that cover the terms of nuclear trade between two trading States in a broad sense including generic legal terms, restrictions and obligations that will apply to all captured trades and activities (e.g. so called ‘deemed exports’ such as intellectual property transfers) between the parties during the term of the agreement. Often, the terms of bilateral agreements are reciprocal between the parties so that both sides have equal legal terms and obligations, though on occasion there may be some asymmetry if agreed to between the sides. Beneath these bilateral agreements are ‘subsequent arrangements’, typically provided as attachments to the agreements, which define additional terms and obligations that apply to specific trades, captured items and activities associated with the bilateral agreement (see Ref. [V.12] for an example). Beneath the bilateral agreements and subsequent arrangements, there are contracts which are required to comply with the terms of these legal trade instruments.

Typically, a State establishes its nuclear trade by negotiating and concluding a series of bilateral agreements with its various supplier and customer States. Thus, the legal structure of trade evolves to meet the needs of a State’s growing nuclear industry through both import and export as the situation may require. This provides for secure supplies to a State, but also commonly conveys obligations, including those associated with safety, security and non-proliferation, to remain in compliance with the bilateral agreements. As nuclear materials, services and equipment are accumulated or distributed through trade, bilateral agreement obligations are also accumulated and distributed. As a result, a sophisticated structure of international legal interdependence forms between States that are legally cooperating on nuclear energy. However, it is important to note that national policy, laws, regulations on import and disposal of foreign radioactive waste and spent nuclear fuel, provisions on transfer and reprocessing of the nuclear material in the bilateral agreements, the disparities between partners on the RD&D capacity, expertise, infrastructure, labour and financing could all act as impediments for effective implementation of international trade and cooperation on nuclear power and nuclear fuel cycle.

In rare cases, there are broader multilateral cooperation agreements. A most notable and sophisticated example is the Treaty establishing the European Atomic Energy Community (Euratom Treaty), signed in 1957 [V.13]. The Euratom Treaty created a common nuclear marketplace and now extends to include all members of the European Union. As a unique and early exemplar of a very broad and sophisticated multilateral cooperation agreement, it is instructive to reproduce its high level task statement (Title I, Art. 1 of Ref. [V.13]):

> "It shall be the task of the Community to contribute to the raising of the standard of living in the Member States and to the development of relations with the other countries by creating the conditions necessary for the speedy establishment and growth of nuclear industries."

Article 2 of Title I [V.13] defines a broad set of actions:

> "In order to perform its task, the Community shall, as provided in this Treaty:
>
> (a) promote research and ensure the dissemination of technical information;
> (b) establish uniform safety standards to protect the health of workers and of the general public and ensure that they are applied;
> (c) facilitate investment and ensure, particularly by encouraging ventures on the part of undertakings, the establishment of the basic installations necessary for the development of nuclear energy in the Community;
> (d) ensure that all users in the Community receive a regular and equitable supply of ores and nuclear fuels;
> (e) make certain, by appropriate supervision, that nuclear materials are not diverted to purposes other than those for which they are intended;
> (f) exercise the right of ownership conferred upon it with respect to special fissile materials;
> (g) ensure wide commercial outlets and access to the best technical facilities by the creation of a common market in specialised materials and equipment, by the free movement of capital for investment in the field of nuclear energy and by freedom of employment for specialists within the Community;
> (h) establish with other countries and international organisations such relations as will foster progress in the peaceful uses of nuclear energy."

There are also examples of narrower multilateral cooperation agreements that are specific to a shared sensitive nuclear fuel cycle technology. Notable examples are the URENCO treaties[10], which define cooperation on technology development and use of certain gaseous centrifuge technology. Moreover, the agreements underlying EURODIF, in France, and the International Uranium Enrichment Center, in the Russian Federation, are additional examples of multilateral cooperation agreements that operate as consortia apart from enrichment technology transfers.

The above summary discussion and very limited set of examples illustrate the existing international legal framework that facilitates bilateral and multilateral, peaceful nuclear energy cooperation between States. If considered superficially, agreements governing international trade and cooperation on nuclear power and fuel cycle may seem to hamper competitive trade as found in less regulated markets. However, peaceful nuclear energy development and trade implies transfer of considerable and unique responsibilities and liabilities. The sophisticated nuclear trade regime helps to manage these specific and unique risks associated with nuclear energy development. The only market with comparable and even more stringent trade law in certain cases, involves military equipment. Although rare, some examples of multilateral agreements (e.g. Euratom Treaty [V.13]), as well as the emerging

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[10] Treaty of Almelo (1970), available at http://fissilematerials.org/library/urenco70.pdf; Treaty of Washington (1992), available at http://fissilematerials.org/library/urenco92.pdf; Treaty of Cardiff (2005), available at http://fissilematerials.org/library/urenco05.pdf; and Treaty of Paris (2011), available at http://fissilematerials.org/library/urenco11.pdf

multiplicity of suppliers and bilateral agreements among certain countries (nuclear power plants, fuel supplies and services) indicate that benefits of competitive trade can be achieved in the future for a variety of supplies in nuclear power and the nuclear fuel cycle, within the established governance models of international nuclear trade and cooperation. International cooperation is also viewed crucial in developing the next generation of nuclear reactors.

The mechanisms of countries' collaboration in nuclear fuel cycle need to be further examined to ensure they will remain sufficient assuming a substantial expansion in the international transfer of spent fuels and related fresh fuels with recycled fissile materials.

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Annex

CONTENTS OF THE CD-ROM

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ABBREVIATIONS

ADS	accelerator driven system
AHWR	advanced heavy water reactor
ALWR	advanced light water reactor
AmBB	americium bearing blankets
ANDRA	National Radioactive Waste Management Agency (Agence nationale pour la gestion des déchets radioactifs)
APWR	advanced pressurized water reactor
ARCAL	Regional Co-operation Agreement for the Promotion of Nuclear Science and Technology in Latin America and the Caribbean
ARCAS	ADS and Fast Reactor Comparison Study
ASN	Nuclear Safety Authority (Autorité de sûreté nucléaire)
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
BAU	business as usual
BN	sodium cooled fast reactor (Russian design)
CANDU	Canada deuterium–uranium
CAREM	Central ARgentina de Elementos Modulares
CEA	French Alternative Energies and Atomic Energy Commission (Commissariat à l'énergie atomique et aux énergies alternatives)
CEFR	China Experimental Fast Reactor
CIEMAT	Research Centre for Energy, Environment and Technology (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas)
CNA	Atucha nuclear power plant (central nuclear Atucha)
CNE	Embalse nuclear power plant (central nuclear Embalse)
CNEA	National Atomic Energy Commission (Comisión Nacional de Energía Atómica)
CP–ESFR	Collaborative Project for a European Sodium Fast Reactor
CVR	coolant void reactivity
DDD	decommissioning, dismantling and waste disposal

DESAE	Dynamic Energy System — Atomic Energy
DUPIC	direct use of spent PWR fuel in CANDU reactors
EDF	Électricité de France
EFIT	European Facility for Industrial Transmutation
EPR	European pressurized water reactor
ESFR	European sodium fast reactor
Euratom	European Atomic Energy Community
FBR	fast breeder reactor
FOAK	first-of-a-kind
FRTh	fast reactor with thorium blankets
FRU	fast reactor with UOX first load
GAINS	Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle
GFR	gas cooled fast reactor
GIF	Generation IV International Forum
HLW	high level waste
HM	heavy metal
HWR	heavy water reactor
ICUE	International Uranium Enrichment Center
IFCC	International Fuel Cycle Centre
ILW	intermediate level waste
INES	innovative nuclear energy system
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IRR	internal rate of return
ISPE	Institute for Studies and Power Engineering
JAEC	Japan Atomic Energy Commission
KAERI	Korea Atomic Energy Research Institute

LCOE	levelized cost of electricity
LFR	lead cooled fast reactor
LLW	low level waste
LUAC	levelized unit lifecycle amortization cost
LUEC	levelized unit energy cost
LUFC	levelized unit fuel cost
LUOM	levelized unit lifecycle operation and maintenance cost
LWR	light water reactor
MELOX	French mélange oxide
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts
MOX	mixed oxide
MSBR	molten salt breeder reactor
MSR	molten salt reactor
OECD NEA	OECD Nuclear Energy Agency
NES	nuclear energy system
NESA	Nuclear Energy System Assessment
NEST	Nuclear Economics Support Tool
NG	non-geographical, non-personified
NOAK	nth-of-a-kind
NPV	net present value
O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development
OKBM	Experimental Design Bureau for Mechanical Engineering
PATEROS	Partitioning and Transmutation European Roadmap for Sustainable Nuclear Energy
PHWR	pressurized heavy water reactor
PNGMDR	National Plan on Management of Radioactive Materials and Waste
PUREX	plutonium and uranium recovery by extraction

PWR	pressurized water reactor
RAR+IR	reasonably assured and inferred resources
RATEN ICN Piteşti	Technologies for Nuclear Energy State Owned Company, Institute for Nuclear Research Piteşti
RD&D	research, development and demonstration
RED-IMPACT	Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Nuclear Waste Disposal
ROI	return on investment
SCE	standard coal equivalent
SCWR	supercritical water cooled reactor
SFR	sodium cooled fast reactor
SMR	small modular reactor
SWU	separative work unit
SYNERGIES	Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability
TEPS	Tool for Energy Planning Studies
UOX	uranium oxide
VHTR	very high temperature reactor
WWER	water cooled, water moderated power reactor
WWER-S	light water reactor with improved characteristics

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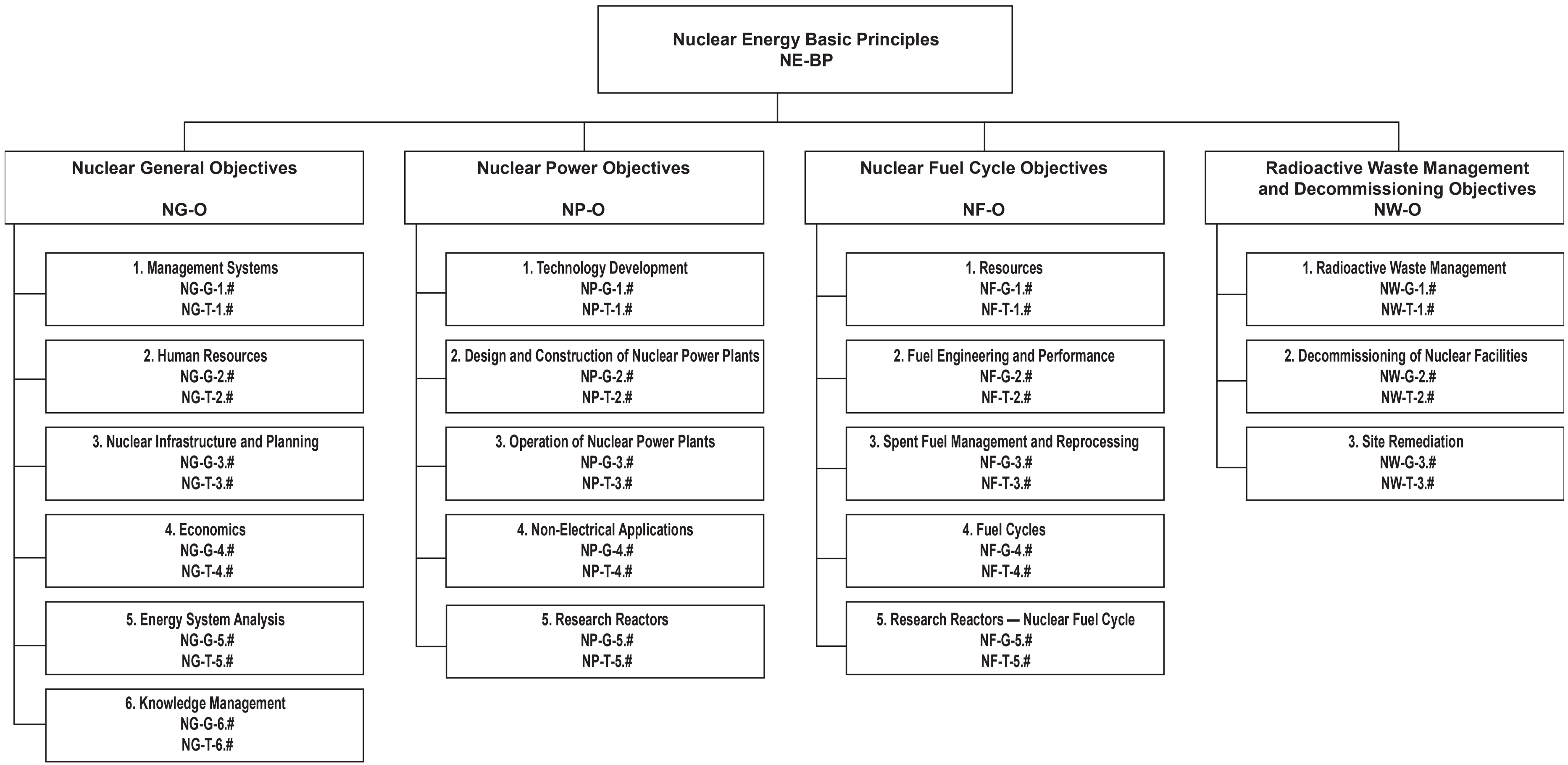

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