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INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Environmental Impact from Depletion of Resources

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INPRO METHODOLOGY FOR SUSTAINABILITY ASSESSMENT OF NUCLEAR ENERGY SYSTEMS: ENVIRONMENTAL IMPACT FROM DEPLETION OF RESOURCES

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IAEA NUCLEAR ENERGY SERIES No. NG-T-3.13

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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 launched in the year 2000, based on resolutions of the IAEA General Conference (GC(44)/RES/21). One of the INPRO objectives is to help to ensure that nuclear energy is available in the twenty-first century in a sustainable manner. To meet this objective, INPRO is proceeding in steps.

In its first step, referred to as Phase 1, INPRO developed a set of basic principles, user requirements and criteria, together with an assessment method, which constitute the INPRO methodology, for the evaluation of a national or global nuclear energy system with regard to its long term sustainability. The methodology was documented in the form of an assessment manual and comprised an overview volume and eight other volumes covering the areas of economics, infrastructure, waste management, proliferation resistance, physical protection, environment, safety of reactors and safety of nuclear fuel cycle facilities. The first edition of this manual was IAEA-TECDOC-1575 Revision 1, published by the IAEA in 2008.

In its second step, referred to as Phase 2, Member States participating in INPRO are performing national and international nuclear energy system assessments using the INPRO methodology. The results of these nuclear energy system assessments up to 2009 are documented in IAEA-TECDOC-1636, published at the end of 2009, which includes several proposals on how to update the INPRO methodology based on the experience of the assessors. In parallel, the INPRO steering committee, IAEA experts and the INPRO group have also developed some proposals for updating the methodology.

All the proposals were evaluated by internal and external experts at an IAEA Consultants Meeting in 2012. Based on the outcome of these consultancies, the INPRO manual was updated. This publication covers the INPRO methodology area of environmental impact from depletion of resources.

The IAEA officers responsible for this publication were A. Korinny and J. Phillips of the Division of Nuclear Power.

CONTENTS

SUMMARY

This publication is an update of Volume 7 of IAEA-TECDOC-1575 Rev. 1 (2008), Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual: Environment. It is based on recommendations presented by Member States participating in the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA experts and the INPRO group.

In this volume of the INPRO manual, guidance is provided on assessing a nuclear energy system (NES) in the area of environmental impact from depletion of resources.

The INPRO methodology in the area of environmental impact from depletion of resources consists of one basic principle, two user requirements and seven criteria.

The basic principle seeks to assure that the NES will be capable of contributing to energy needs in the twenty-first century while making efficient use of non-renewable resources that it requires for construction, operation and decommissioning.

The first user requirement UR1 seeks to confirm that the NES assessed will not run out of resources such as fissile and fertile materials and other non-renewable materials during its lifetime. Additionally, the NES should make efficient use of the non-renewable resources. To achieve these objectives, the designer is asked to improve the efficiency of natural uranium and other key material use in the NES assessed in comparison with existing NESs (operating as of 2013). The operator of the NES is asked to confirm that sufficient resources of fissile/fertile materials and other key materials are available during the intended lifetime of the system. The INPRO assessor should confirm that the designer, as well as the operator, has succeeded in meeting these objectives.

A global market exists to provide sufficient resources of fissile and fertile materials, which necessitates a global assessment of their availability. Recognizing that such an assessment is beyond the reasonable capacity of an individual country, this publication provides background material and summarizes the results of some international global assessment studies that can be referred to and referenced in national assessments.

The background material provided includes analyses of global supply and demand of fissile/fertile materials and non-renewable materials, a summary of a recently completed study on global architectures of innovative NESs with thermal and fast reactors and a closed nuclear fuel cycle, and simple tools to assess the efficiency of uranium use.

The second user requirement UR2 asks the designer to confirm that the NES to be installed will, within a reasonably short time after startup, produce more power than that needed for construction of the system.

1. INTRODUCTION

This publication is an update of Volume 7 of the report IAEA-TECDOC-1575 Rev. 1 (2008), Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual: Environment [1]. It is based on recommendations presented by Member States participating in the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA experts and the IAEA/INPRO group.

The information presented in the updated overview of the INPRO methodology[1] should be considered to be an integral part of this publication, and the user should be familiar with that information.

1.1. BACKGROUND

Applying the INPRO methodology in an assessment of a nuclear energy system (NES) is a bottom up exercise, and consists of determining the value of each of the INPRO methodology indicators (INs) of the criteria (CR) and comparing the value with the corresponding acceptance limit (AL) of the given CR. Based on the comparison, a judgement on the potential, i.e. the capability of an NES to comply with the CR, is made.

The ultimate goal of the application of the INPRO methodology is to confirm that the NES assessed fulfils all the CR and hence the user requirements (URs) and basic principles (BPs) and therefore represents a long term sustainable system for a Member State (or group of Member States). BPs, URs and CR have been defined in different areas: economics, infrastructure, waste management, proliferation resistance, physical protection, environmental impact of stressors, environmental impact from depletion of resources and nuclear safety.

One possible output from an assessment is the identification of areas where a given NES needs to be improved. Given the comprehensive nature of an assessment using the INPRO methodology, such an assessment would be expected to indicate clearly the specific attributes of an NES that need to be improved.

1.2. OBJECTIVE

This volume of the updated INPRO manual provides guidance to the assessor of an NES (or a facility thereof) that is to be installed, describing how to apply the INPRO methodology in the area of environmental impact from depletion of resources. The INPRO assessment should enable either the confirmation of adequate environmental performance by the NES, i.e. fulfilment of all INPRO methodology environmental CR, or the identification of gaps (non-compliance with the INPRO methodology CR) requiring corrective actions (including research, development and demonstration (RD&D)) to achieve long term sustainability of the NES assessed.

The INPRO assessor (or team of assessors) is assumed to be knowledgeable in the area of environmental impact from depletion of resources and/or may be using the support of qualified national or international organizations (e.g. the IAEA) with relevant experience.

Two general types of INPRO assessors can be distinguished: a designer (supplier or developer) of nuclear technology, i.e. a nuclear technology holder, and a (potential) user of such technology.

The role of the latter type of assessor, i.e. a technology user, is primarily to check, in a simple manner, whether the designer (supplier) has appropriately taken into account the resource aspects in their design as defined by the INPRO methodology. A technology user is assumed, in order to minimize their risk, to be primarily interested in proven technology to be installed in their country.

A designer (developer) performing an INPRO assessment can also use this current publication to check whether the (innovative) design under development meets the INPRO methodology requirements, but can additionally initiate modifications during early design stages, if necessary, to improve the performance of the design.

An assessor in a country embarking on a nuclear power programme could use the INPRO methodology in a so called graded approach, depending on the stage of the programme (see overview of the INPRO methodology[1]).

[1] A publication on this subject is in preparation.

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

Environmental impact from an NES involves two large groups of factors. The first group comprises radiological, chemical, thermal and other stressors which NESs release into environment. This group also includes water intake because this factor can be important for biota even when this water is returned to the environment in a clean form (e.g. as steam from NPP cooling towers). All these factors are considered in the INPRO methodology manual on environmental impact of stressors [2].

The second group of factors impacting the environment comprises the consumption of non-renewable resources including both fissile/fertile materials necessary to produce nuclear fuel and other materials (e.g. zirconium). All these factors and consumption of electricity necessary to construct, operate and occasionally decommission NES installations are considered in this updated INPRO methodology manual on environmental impact from depletion of resources.

1.4. STRUCTURE

In Section 2, general features of an environmental assessment on the impact of depletion of resources and an overview of information that must be available to an INPRO assessor to perform assessment are presented.

In Section 3, the background of the INPRO methodology BP for environmental impact from depletion of resources, and the corresponding URs and CR, consisting of INs and ALs, are presented. At the CR level, guidance is provided on how to determine the value of the IN and AL.

Appendix I summarizes information on global demand and supply of fissile and fertile materials.

Appendix II presents information on global demand and supply of non-renewable materials (other than fissile and fertile materials).

Appendix III summarizes relevant results of the INPRO collaborative project on Global Architectures of Innovative Nuclear Energy Systems with Thermal and Fast Reactors, Including a Closed Fuel Cycle (GAINS) [3], and provides references to some other studies that reflect upon uranium supply and demand in particular global NES evolution scenarios [4].

Appendix IV presents the results of an evaluation of the mass balance of an NES focusing on the front end of the fuel cycle. The tool used for the evaluation is the NESA Economic Support Tool (NEST) described in the INPRO methodology manual on economics [5] (NESA stands for nuclear energy system assessment).

1.5. OVERVIEW OF THE STRUCTURE OF INPRO METHODOLOGY REQUIREMENTS

Table 1 provides an overview of the BP, URs and CR in the INPRO methodology area of environmental impact from depletion of resources.

TABLE 1. OVERVIEW OF BASIC PRINCIPLE, USER REQUIREMENTS AND CRITERIA IN THE INPRO METHODOLOGY AREA OF ENVIRONMENTAL IMPACT BY DEPLETION OF RESOURCES

INPRO basic principle (availability of resources): A nuclear energy system (NES) shall be capable of contributing to the energy needs in the twenty-first century while making efficient use of non-renewable resources*

User requirement (UR)	Criteria (CR)	Indicator (IN) and acceptance limit (AL)
UR1: Consistency with resource availability: The NES should be able to contribute to the world's energy needs during the twenty-first century without running out of fissile/fertile material and other non-renewable materials, with account taken of reasonably expected uses of these materials external to the NES. In addition, the NES should make efficient use of non-renewable resources	CR1.1: Fissile/fertile material	IN1.1: Quantity, $F_j(t)$, of fissile/fertile material type j available for use in the NES at time t AL1.1: $F_j(t) > D_j(t)$, quantity available for NES, $F_j(t)$, should be bigger than quantity needed, $D_j(t)$, for any $t < 100$ years
	CR1.2: Non-renewable materials	IN1.2: Quantity, $Q_i(t)$, of material type i available for use in the NES at time t AL1.2: $Q_j(t) > D_j(t)$, quantity available for NES, $Q_j(t)$, should be bigger than quantity needed, $D_j(t)$, for any $t < 100$ years
	CR1.3: Power supply to NES	IN1.3: $P(t)$ = power available (from both internal and external sources) for use in the NES at time t AL1.3: $P(t) \geq P_{\mathrm{NES}}(t)$, for any $t < 100$ years, where $P_{\mathrm{NES}}(t)$ is the power required by the NES at time t
	CR1.4: End use of uranium	IN1.4: U_{eu} = end use (net) energy (GW·h) delivered by the NES per tonne of uranium mined AL1.4: $U_{eu} > U_0$; U_0 = maximum achievable end use for an existing NES** with a once through (open) fuel cycle
	CR1.5: End use of thorium	IN1.5: Th_{eu} = end use (net) energy (GW·h) delivered by the NES per tonne of thorium mined AL1.5: $Th_{eu} > Th_0$; Th_0 = maximum achievable end use for a current operating thorium cycle
	CR1.6: End use of non-renewable resources	IN1.6: C_i = end use (net) energy delivered by the NES per tonne of limited non-renewable resource i consumed AL1.6: $C_i > C_0$; C_0 to be determined on a case specific basis
UR2: Adequate net energy output: The energy output of the NES should exceed the energy required to implement, operate and decommission the NES within an acceptably short period	CR2.1: Amortization time	IN2.1: T_{EQ} = time required to match the total energy input into the NES with energy output (years) AL2.1: $T_{\mathrm{EQ}} \ll T_{\mathrm{L}}$; T_{L} = intended lifetime of NES

* Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

** In the updated INPRO methodology, 'existing NES' means an 'NES of latest design operating in 2013'.

1.6. CONCEPT OF SUSTAINABLE DEVELOPMENT AND ITS RELATIONSHIP WITH THE AREA OF ENVIRONMENTAL IMPACT FROM DEPLETION OF RESOURCES OF THE INPRO METHODOLOGY

The United Nations World Commission on Environment and Development Report [6] (often known as the Brundtland Report), entitled Our Common Future, defines sustainable development as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (see chapter 2, paragraph 1 [6]). Moreover, this definition contains within it two key concepts:

— "the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and
— the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."

This simple definition of sustainable development suggests a three part test for any approach to sustainability and sustainable development: (i) current development should be fit for the purpose of meeting current needs with minimized environmental impacts and acceptable economics; (ii) current RD&D programmes should establish and maintain trends that lead to technological and institutional developments that serve as a platform for future generations to meet their needs; and (iii) the approach to meeting current needs should not compromise the ability of future generations to meet their needs.

At first reading, this definition may appear obvious, but when considering the complexities of implemented nuclear energy technology and systems, plus their many supporting institutions, meeting the three part test is not always straightforward because many approaches only meet one or perhaps two parts of the test in a given area, and may fail on the others.

The Brundtland Report overview (para. 61 [6]) of the topic of nuclear energy summarized that:

> "After almost four decades of immense technological effort, nuclear energy has become widely used. During this period, however, the nature of its costs, risks, and benefits have become more evident and the subject of sharp controversy. Different countries world-wide take up different positions on the use of nuclear energy. The discussion in the Commission also reflected these different views and positions. Yet *all agreed that the generation of nuclear power is only justifiable if there are solid solutions to the unsolved problems to which it gives rise. The highest priority should be accorded to research and development on environmentally sound and ecologically viable alternatives, as well as on means of increasing the safety of nuclear energy.*"

The Brundtland Report presented its comments on nuclear energy in chapter 7, section III [6]. In the area of nuclear energy, the focus of sustainability and sustainable development is on solving certain well known problems (referred to here as 'key issues') of institutional and technological significance. Sustainable development implies progress and solutions in the key issue areas. Seven key issues are discussed (in this order):

(a) Proliferation risks;
(b) Economics;
(c) Health and environment risks;
(d) Nuclear accident risks;
(e) Radioactive waste disposal;
(f) Sufficiency of national and international institutions (with particular emphasis on intergenerational and transnational responsibilities);
(g) Public acceptability.

The INPRO methodology for the self-assessment of sustainability and sustainable development of a NES is based on the broad philosophical outlines of the Brundtland Report's concept of sustainable development described above. Twenty-eight years have passed since the publication of the Brundtland Report, and 14 years have passed since the initial consultancies on development of the INPRO methodology in 2001. In the interim period of time, significant historical events have starkly highlighted certain key issues. However, the key issues for sustainable development of NESs have remained essentially unchanged over nearly three decades.

By far the most notable events in the period, which have a direct impact on nuclear energy sustainability, are related to non-proliferation, nuclear security, cost escalation of new construction and, most notably, the accident at the Fukushima Daiichi nuclear power plant in 2011. The Fukushima Daiichi accident further clarified that nuclear safety is an issue of paramount importance for sustainability and that external hazards, associated with a particular site, could be responsible for a dramatic common cause failure involving multiple reactor units.

In each INPRO methodology manual, a key issue of NES sustainable development is examined. The structure of the methodology is a hierarchy of INPRO BPs, URs and CR measuring whether the UR has been achieved. Under each BP, the CR include measures that take into consideration the three part Brundtland Report's sustainable development test.

This INPRO manual focuses on the key issue of environmental impact through depletion of natural resources associated with NES development and deployment. The Brundtland Report did not specifically identify depletion of resources as a key issue in 1987. There are several reasons why these issues might have been omitted at the time, which still exist today. These reasons are described below.

In a broad and general sense, NESs are frugal with respect to the use of natural resources when compared to available dispatchable, baseload non-NESs. For example, it is unlikely that significant and sustainable pressure will come to bear on natural uranium fuel resources until the second half of the current century or well beyond that, depending on global nuclear energy growth and further discoveries of economically recoverable uranium resources. When uranium fuel becomes sufficiently expensive, closed fuel cycles can produce many thousands of years of nuclear fuel from existing fertile material resources. As the nuclear fuel cost is very low, taken as a fraction of the nuclear electricity cost, significantly more expensive nuclear fuel is likely to be acceptable, depending upon how a particular nuclear market is structured.

The more complex sustainability questions in the area of resource depletion pertain to use of other mineral resources that are rarer than nuclear fuels (e.g. critical minor constituents in metal alloys and other materials that are particular to nuclear energy technology). However, if a country decides that its NES should depend wholly upon its own mineral resources, rather than the international market, in some cases, this may also imply more severe limits to nuclear fuel sustainability. Questions about when and how diversification from a uranium fuel economy should expand to include a growing share of other nuclear fuels are more associated with development of roadmaps for reactor and fuel cycle technology development and deployment than they are with ultimate resource depletion. Even so, that progress is being made (or is planned) to achieve more effective fuel utilization is important, particularly for time periods extending well into the second half of this century. Essentially, indefinite and irretrievable direct geological disposal of once through uranium and thorium fuels may imply an unsustainable NES in the longer term. It also may also damage future nuclear fuel resource economics to a degree that it impugns nuclear energy as an option available to future generations, thus failing a key Brundtland Report test of sustainability.

This INPRO manual tests whether or not an NES is sustainable with respect to fissile/fertile and non-renewable material resources within a period of a century. It also tests whether or not greater net end use energy is being (or planned to be) produced from mined uranium and thorium than the maximum achievable under current open fuel cycles. Taken together, these measures directly address the question of whether NESs, implemented to meet current needs, are having minimum intergenerational impact from the perspective of natural resource depletion, thus satisfying the three part Brundtland Report sustainable development test.

2. GENERAL FEATURES AND NECESSARY INPUT FOR AN ASSESSMENT

This section provides some general background information on environmental issues, particularly on the environmental impact from depletion of resources caused by an NES. The necessary input and its sources for an assessment of an NES in the INPRO methodology area of environmental impact from depletion of resources are also defined.

2.1. CONCEPT OF SUSTAINABLE DEVELOPMENT

The concept of sustainability can be considered from several related, but different, points of view: social, economic, environmental and institutional. This publication deals with the environmental dimension of sustainability, by considering issues related to depletion of natural resources.

Protection of the environment is a major consideration in the processes for approving industrial activities in many countries. The level of international societal concern for the environment is clearly indicated in publications reflecting international consensus, notably the Brundtland Report [6], the Rio Declaration on sustainable development [7] and the Joint Safety Convention of the IAEA [8].

The common basic idea in these publications is that the present generation should not compromise the ability of future generations to fulfil their needs and should leave them with a healthy environment. Nuclear power should support sustainable development by providing much needed energy with relatively low burdens on the atmosphere, water, land and resource use. Efficient and effective use of resources will be necessary. Moreover, improvement of the technology should include improvement of its environmental aspects to a degree that is consistent with importance to society and with the potential environmental performance of competing technologies.

2.2. INTERFACES OF A NUCLEAR ENERGY SYSTEM WITH THE ENVIRONMENT

The different components or facilities of a complete NES are presented in Fig. 1, starting with mining and processing, through to the final disposal of nuclear waste.

An NES has several interfaces with the environment and other industries. From the environment, non-renewable resources such as fissile and fertile materials, e.g. uranium and thorium (orange arrow in Fig. 1), are removed and used in the NES together with other materials such as zirconium (bright yellow arrow in Fig. 1). On the other hand, the NES produces some stressors, e.g. release of radioactive nuclides, that have an adverse impact on the environment (pale yellow arrow in Fig. 1).[2]

In addition to these environmental effects, an NES is exchanging with other industries the energy and industrial materials required for the installation, operation and finally decommissioning of the nuclear facilities (blue arrow in Fig. 1).

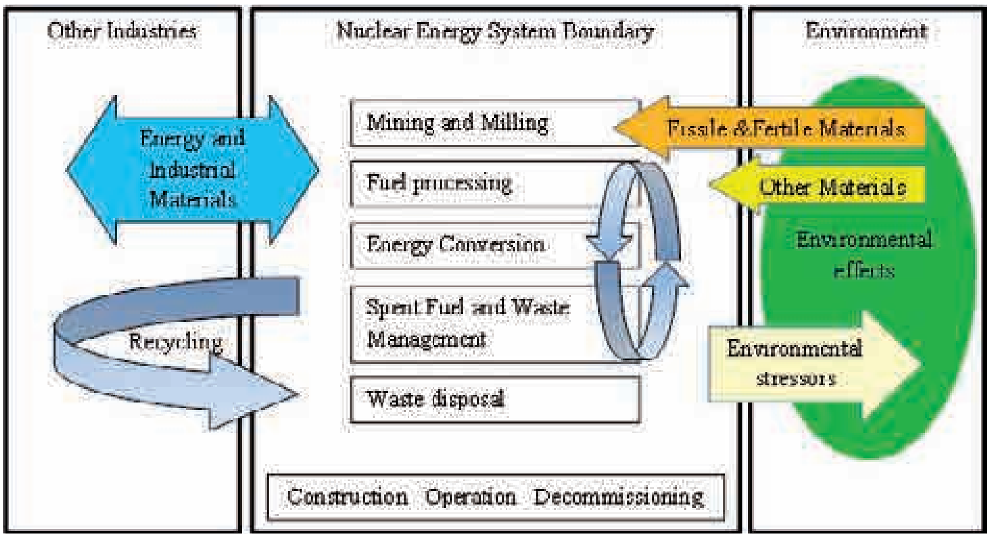

FIG. 1. Interfaces of a nuclear energy system with the environment [1].

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[2] The issue of stressors is covered in a separate report of the updated INPRO manual called Environmental Impact of Stressors. This report is in preparation.

Ideally, an environmental impact assessment of an NES takes all these interfaces into account during the lifetime of the system.

2.3. SPECIFICATION OF THE NUCLEAR ENERGY SYSTEM

A prerequisite for an INPRO assessment is the specification of the NES (see overview of the INPRO methodology) to be assessed. The NES is to be defined by the INPRO assessor.

For an environmental assessment, in principle, the following aspects should be covered in the specification of the NES:

- The complete NES should be considered, covering the entire front end of the fuel cycle, the energy conversion unit (reactor) and the entire back end comprising waste repositories. For all nuclear facilities, the complete lifetime should be covered, i.e. construction, operation and decommissioning.
- If necessary, environmental burdens may be divided into national (or regional) burdens and those occurring outside the country (or regional) borders, if such information would be required by stakeholders.

Thus, by meeting the above defined requirements, the general underlying principle of assessing the entirety of the environmental impacts would not be violated.

However, in general, cut-offs, i.e. selection of specific facilities of an NES, will be required in an INPRO assessment. Such an approach is recommended for nuclear technology users and specifically in the case that a country is embarking on a nuclear power programme, i.e. the INPRO environmental assessment in such a country should cover only the first nuclear power plant and related waste management facilities. A nuclear technology developer may focus the environmental assessment (analysis) on their design of a nuclear facility under development.

2.4. INFORMATION ON DEMAND AND SUPPLY OF RESOURCES

To assess criterion CR1.1 of UR1, several generic studies are available that define the global demand and the availability of primary (and secondary, if a global market exists for it) supply of natural uranium (and other fissile materials) needed for nuclear facilities within the next 100 years. These studies, presented in Appendices I–IV, cover different development rates of demand and different fuel cycles.

To assess criterion CR1.2 of UR1, the results of a generic study for global demand and supply of other key materials in an NES are needed to complete an INPRO assessment. A recently performed generic study on global supply and demand of non-renewable materials is summarized in Appendix II, and could be used as reference in the assessment.

To assess criterion CR1.3 of UR1, information about the power needed to construct, operate and decommission a typical nuclear power plant currently operating is available, but for the NES assessed, this information is to be provided by the (potential) supplier.

To assess criterion CR1.4 and criterion CR1.5 of UR1, the net energy delivered by the NES assessed per tonne of uranium and thorium used is to be calculated. For uranium, this value can be determined by the INPRO assessor using a simplified tool, if the assessor has access to the specific characteristics of the assessed NES, such as the thermal efficiency and core average burnup of the nuclear power plant to be installed in the country.

To assess criterion CR1.6 of UR1, the end use of key materials (other than fissile and fertile materials) needed in the NES assessed and in the current NES is to be determined. For such a study, close cooperation between the assessor and the (potential) supplier is necessary. For some key materials, the results of generic studies on a current NES are available.

To assess criterion CR2.1 of UR2, a reference study is available that defines the energy payback time (EPBT) for a typical currently operating NES.

2.5. OTHER SOURCES OF INPUT

A comprehensive INPRO assessment of the planned NES in the Republic of Belarus has been performed between 2009 and 2011, and is documented in Ref. [9].

3. INPRO BASIC PRINCIPLE, USER REQUIREMENTS AND CRITERIA

This section presents the BP, the URs and the CR in the INPRO methodology area of environmental impact caused from depletion of resources.

3.1. INPRO BASIC PRINCIPLE: AVAILABILITY OF RESOURCES

INPRO basic principle: The NES shall be capable of contributing to the energy needs in the twenty-first century while making efficient use of non-renewable resources.[3]

To be environmentally acceptable, the NES assessed must be sustainable and not run out of important resources part way through its intended lifetime. These resources include fissile/fertile materials, water (when supplies are limited or quality is under stress) and other critical materials. The NES should also use them at least as efficiently as acceptable alternatives, both nuclear and non-nuclear. Even in the absence of a viable alternative, the best use possible is to be made of non-renewable resources.

Sustainability of an NES requires primarily that it fits its purpose. This has different aspects, which are addressed separately within the different INPRO methodology areas (e.g. economics, safety). All aspects should be considered, and the designer and operator of the system should strive to achieve optimal conditions with minimal effects on the environment, for which compromises across the areas may be necessary. Thus, the INPRO methodology requires a holistic approach, i.e. the whole NES should be considered in all areas, and all material flows in and out of the NES should be accounted for, including resources taken from, as well as stressors emitted to, the environment.

The INPRO methodology has defined two URs, UR1 and UR2, for the BP.

3.2. USER REQUIREMENT UR1: CONSISTENCY WITH RESOURCE AVAILABILITY

User requirement UR1: The NES should be able to contribute to the world's energy needs during the twenty-first century without running out of fissile/fertile material and other non-renewable materials, with account taken of reasonably expected uses of these materials external to the NES. In addition, the NES should make efficient use of non-renewable resources.

UR1 addresses continuous availability and consumption of non-renewable resources. Primarily, it should be demonstrated that the NES assessed will operate throughout the twenty-first century without incurring fuel shortages and lack of strategic materials. The time horizon of about 100 years was chosen in the INPRO methodology based on the consideration that beyond this period, uncertainties become too large in any evaluation result.

To demonstrate that this UR is met, careful consideration should be given to the implications of available resources with appropriate choice of the boundary of the NES assessed (see Fig. 1). The availability and consumption of resources generally require a global, rather than an individual national or regional, evaluation.

[3] Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

In addition, resources considered, especially those of fissile/fertile materials, need to include estimated resources beyond those currently fully proven. When addressing unconventional sources (e.g. uranium coextraction with phosphates or extraction of uranium from sea water (see Appendix I for more information)), the assessor should bear in mind that such unconventional resources of fissile/fertile materials may have implications not only on the environment, but also on the costs of nuclear fuel.

Global, regional and national energy demand/supply scenarios

To address UR1, it needs, in principle, to be demonstrated that the NES demand for non-renewable resources can be supplied at any time that the NES is operated during the twenty-first century, considering the entire lifetime (commissioning, operation and decommissioning) of all its facilities. As a global market exists and is likely to continue existing for all NES related non-renewable resources, such a demonstration generally requires a global analysis that is beyond the reasonably expected capability of any individual country performing an NES assessment. The way forwards here may be twofold.

One way is to borrow from the results of the recently completed international studies on global availability of non-renewable resources; in order to facilitate this method, Appendices I–IV are included in the current publication, where the main results of such studies and the approaches used are highlighted and summarized, complete with a list of references to full reports on these studies.

On the other hand, if a country performing the NES assessment has great plans for its nuclear energy programme and foresees it could eventually become a major player in global nuclear energy markets, then it makes sense to consider joining efforts with other countries to perform an updated global resource availability assessment. Such assessments are being periodically undertaken under the aegis of renowned international organizations, and one option to do so is to join the activities of the IAEA/INPRO task ‘Global scenarios’.

Notwithstanding the existence of a global market for NES related non-renewable resources, national assessment also makes sense once the country considers ensuring that its national nuclear power programme benefits from its own domestic resources. Assessment of this kind will be useful for understanding the national resource base and national economy potential, if only in the medium and long terms, but it will only partially support the assessment against the UR1 requirement.

Regional assessment could be recommended in the case of existing or foreseen long term partnerships with particular neighbouring or non-neighbouring countries with which good relations and cooperation in the nuclear energy field exist. Such an assessment could foster further cooperation, potentially resulting in a sustainable regional NES; however, as in the case of a national assessment, it would only partially support the assessment against UR1.

In both national and regional assessments, the missing ‘rest of the world’ information could be retrieved from the already completed resource availability studies such as those presented in the appendices to this publication.

Summarized below are the factors that are important for non-renewable resource availability assessment of relevance to UR1.

For an INPRO assessment of the environmental impact from depletion of resources, the global and national (regional) scenarios of nuclear capacity growth first need to be specified, including data on time dependent capacity additions and corresponding reactor types. To obtain an idea of possible global scenarios, the information presented in Refs [3, 4] may be useful. These studies provide a range of plausible (and even some idealistic) global nuclear energy capacity increases, and following several scenarios within the range may aid in understanding how the existing large uncertainties could affect the results of a UR1 INPRO assessment.

Also useful could be an analytical framework for material flow analyses developed within the collaborative project GAINS. This framework, presented in Ref. [3], includes internationally verified data for many existing and future reactors, descriptions of closed fuel cycles, storylines and scenarios of global nuclear energy development up to the end of this century, results of cross-verification and recommendations on the use of material flow analysis codes, and other relevant information.

The INPRO methodology defines six CR (CR1.1–CR1.6) for UR1, as shown in Table 2.

TABLE 2. CRITERIA FOR USER REQUIREMENT UR1

User requirement (UR)	Criteria (CR)	Indicator (IN) and acceptance limit (AL)
UR1: Consistency with resource availability: The NES should be able to contribute to the world's energy needs during the twenty-first century without running out of fissile/fertile material and other non-renewable materials, with account taken of reasonably expected uses of these materials external to the NES. In addition, the NES should make efficient use of non-renewable resources	CR1.1: Fissile/fertile material	IN1.1: Quantity, $F_j(t)$, of fissile/fertile material of type j available for use in the NES at time t AL1.1: $F_j(t) > D_j(t)$, quantity available for NES, $F_j(t)$, should be bigger than quantity needed, $D_j(t)$, for any $t < 100$ years
	CR1.2: Non-renewable materials	IN1.2: Quantity, $Q_i(t)$, of material type i available for use in the NES at time t AL1.2: $Q_j(t) > D_j(t)$, quantity available for NES, $Q_j(t)$, should be bigger than quantity needed, $D_j(t)$, for any $t < 100$ years
	CR1.3: Power supply to NES	IN1.3: $P(t)$ = power available (from both internal and external sources) for use in the NES at time t AL1.3: $P(t) \geq P_{NES}(t)$, for any $t < 100$ years, where $P_{NES}(t)$ is the power required by the NES at time t
	CR1.4: End use of uranium	IN1.4: U_{eu} = end use (net) energy (GW·h) delivered by the NES per tonne of uranium mined AL1.4: $U_{eu} > U_0$; U_0 = maximum achievable end use for an existing NES* with a once through (open) fuel cycle
	CR1.5: End use of thorium	IN1.5: Th_{eu} = end use (net) energy (GW·h) delivered by the NES per tonne of thorium mined AL1.5: $Th_{eu} > Th_0$; Th_0 = maximum achievable end use for a current operating thorium cycle
	CR1.6: End use of non-renewable resources	IN1.6: C_i = end use (net) energy delivered by the NES per tonne of limited non-renewable resource consumed AL1.6: $C_i > C_0$; C_0 to be determined on a case specific basis

* In the updated INPRO methodology, 'existing NES' means an 'NES of latest design operating in 2013'.

3.2.1. Criterion CR1.1: Fissile/fertile material

Indicator IN1.1: $F_j(t)$*, quantity of fissile/fertile material of type* j *available for use in the NES at time* t.

Acceptance limit AL1.1: $F_j(t) > D_j(t)$*, quantity available for NES,* $F_j(t)$*, should be bigger than quantity needed,* $D_j(t)$*, for any* $t < 100$ *years.*

3.2.1.1. Types of resources of fissile and fertile materials

In order for an NES to operate successfully, i.e. to contribute to satisfying the world's energy needs during the twenty-first century without running out of resources, UR1 must be primarily applied to fissile/fertile materials, i.e. compliance must be demonstrated with CR1.1, confirming that the quantity of fissile/fertile material type j available at time t will always be more than needed in the NES assessed at any time t during a period of 100 years.

A *fissile material* is one that is capable of sustaining a chain reaction of nuclear fission. The principal fissile materials are ^{235}U (0.7% of naturally occurring uranium), ^{239}Pu, ^{241}Pu and ^{233}U, with the last three being artificially produced from the fertile materials ^{238}U and ^{232}Th. A *fertile material*, not itself capable of undergoing fission by neutrons, is one that decays into fissile material after neutron absorption. Fertile materials are ^{232}Th, which can be converted into fissionable ^{233}U, and ^{238}U, which can be converted into fissionable ^{239}Pu.

In general, two kinds of sources of fissile/fertile materials are distinguished: *primary resources* and *secondary supply*; the latter is also sometimes called the secondary source. Estimations of the availability of such resources can be found in a diverse set of publications by national and international organizations. Table 3 gives an overview of types of resources of fissile and fertile materials, and the references from which information can be retrieved.

TABLE 3. TYPES OF FISSILE/FERTILE MATERIALS AND REFERENCES

Resources of fissile/fertile materials	References
Primary resources[a]	
Natural uranium Natural thorium	Appendix I; Refs [10, 11]
Secondary supply	
Depleted uranium (including its re-enrichment)	Appendix I; Ref. [11]
Natural uranium inventory (governmental and commercial) drawdown	Appendix I; Ref. [11]
Highly enriched uranium available for down blending (with depleted uranium essentially)	Appendix I; Ref. [11]
Reprocessed uranium	Refs [11, 12]
Plutonium from reprocessing of civil spent uranium fuel Plutonium from the surplus military Pu stock Spent nuclear fuel available for reprocessing Transuranium elements in spent fuel retrievable for later use Separated minor actinides (Np, Cm and Am) stock Uranium-238 produced by reprocessing of Th fuel	National data[b]; Appendix I

[a] These primary resources are still to be mined, i.e. they are not yet recovered from their natural environment, but due account is taken of the losses that mining would entail, i.e. these resources represent the net available resources that would be available after mining.
[b] ‘National data’ indicates that no international referenced data are available in the public domain.

The availability of fissile/fertile materials should be considered according to different scales. As has already been mentioned, because the *primary resources* of uranium and thorium are available via a global market, the availability of *primary resources* needs to be considered in an INPRO assessment on a global scale. However, most of the *secondary supply* is available on a national (or regional) scale only, and can, therefore, be considered only by individual Member States in national or regional assessments.

Of the *secondary uranium sources*, depleted uranium produced at enrichment facilities, natural uranium withdrawn from inventories held by utilities and governments, and separated irradiated uranium (reprocessed uranium (REPU)) produced in reprocessing facilities could be used in (partly) closed nuclear fuel cycles and are also available on a global market because of the ease of transportation of these materials.

Transuranics (TRUs), i.e. plutonium, and minor actinides (MAs) resulting from reprocessing of civil spent uranium based fuel, are today part of national NESs with a (partly) closed nuclear fuel cycle and are currently absent from any global market mechanism trading these materials. The possible transfer of such TRUs from outside into an NES has been taken into account in studies presented in Appendices II and III, looking very far into the future, i.e. covering a time period until the end of the century. The same applies to the spent fuel amount and the TRUs contained in that spent fuel.

Plutonium originating from surplus military stocks should be considered on a national scale, because of the limited availability of this resource based on bilateral contracts between certain Member States.

Thorium resources

There is still less known about the *primary thorium resources* compared to the uranium resources. Large thorium resources are found in Australia, Brazil, Canada, China, Egypt, India, Norway, Russian Federation, South Africa, Turkey, United States of America (USA) and the Bolivarian Republic of Venezuela. Existing estimates of thorium resources total more than 6.5 Mt Th. These estimates are considered conservative because the historically weak demand has limited thorium exploration [13].

Classification of primary resources according to their recoverability defined by the IAEA and the OECD Nuclear Energy Agency (OECD/NEA) is described in Appendix I.

Secondary uranium supply

It is generally expected that the role of global *secondary uranium supply* will diminish during the coming decades due to drawdown of natural uranium inventories and the limited availability of military plutonium to be used in a limited number of reactors. Currently, the main global secondary supply is based on down blending of highly enriched uranium (HEU), and in the medium term, re-enrichment of depleted uranium as long as the economic balance of this option versus virgin uranium mining remains attractive.

In case the NES assessed by an INPRO assessor might not be installed before the year 2030 or later, the impact of global secondary supply is likely to be limited. Therefore, in such a case, the INPRO assessment may not need to take into account the global secondary supply, except for, possibly, the re-enrichment of depleted uranium, depending on its economic viability and the availability of enrichment capacity. Above all, if nuclear energy is to remain an option for the longer term, renewal of exploration and opening of new mineable uranium resources have to be relaunched in order to supply most and soon all of the uranium requirements for the global nuclear reactor fleet.

3.2.1.2. Balance of demand and available resources of fissile/fertile materials

Criterion CR1.1 demands two considerations:

— Knowledge of the amount of fissile/fertile *material available* for the NES assessed. These available resources consist of global and national (regional) resources of fissile and fertile materials, including plutonium in the case of a closed fuel cycle, or ^{233}U in a fuel cycle using thorium as the fertile material.
— Knowledge of the amount of fissile/fertile *material needed* in the NES assessed. This demand for resources consists of fissile/fertile materials *entering* the NES, i.e. being supplied as reload fuel.

Estimation of available amount of global primary uranium resources

Appendix I presents the status of available fissile and fertile materials based on the ‘Red Book’, a joint report by the IAEA and OECD/NEA [13].[4] As of 2011, there were ~12×10^6 tonnes of natural uranium (tU) available in the cost category of <US $130, and ~$18 \times 10^6$ tU in the cost category of <US $260, defined as conventional resources. In addition to these conventional resources, there are estimated resources of the same order of magnitude defined as unconventional uranium resources that include uranium found in phosphates and black shale, with estimated prices slightly above the ones for conventional resources.

Uranium contained in sea water would be available in an amount greater than 4×10^9 tU, although at a significantly higher price. Appendix I emphasizes the fact that the uranium supply is based on a global free market that reacts appropriately to higher prices because of expected shortages by increased exploration and production capacity.

[4] Appendix I also presents summaries of some other studies that are relevant to this issue.

Long term perspective of global demand for primary resources of fissile and fertile materials

In Appendix I, which contains a summary of the 2011 edition of the Red Book [13], the demand for natural uranium for the global NES up to 2035 is estimated. In Appendix III, a summary of a more recent comprehensive study regarding global demand for primary fissile/fertile resources until the end of the twenty-first century is presented, which takes into account several parameters such as different types of fuel cycles, different types of reactors, different rates of installation of nuclear facilities, etc. This generic study and the analytical framework developed within it can be used as a basis for all INPRO assessments of the environmental impact from depletion of resources.

Estimation of available amount of national (regional) primary resources of fissile and fertile materials

These data should be available in the country (countries) where the NES assessed is (to be) installed. The INPRO assessor should refer to publications of responsible national (or regional) organizations to get this input. Alternatively, the INPRO assessor can use some publications from international organizations such as the OECD/NEA–IAEA Red Book [13] and the IAEA Integrated Nuclear Fuel Cycle Information System (INFCIS) [10] that also list these resources based on a national estimation.

Long term perspective of national (regional) demand for resources of fissile and fertile materials

This input should be available to the INPRO assessor for the country (countries) where the NES is (to be) located. The NES demand for resources depends on the national (regional) scenario (e.g. rate of installation and types of nuclear facilities) of nuclear power introduction (or expansion), and, thus, the establishment of a national (regional) nuclear power scenario is a prerequisite to preparing this input (i.e. creation of such a national nuclear scenario is a prerequisite for an INPRO assessment).

To determine the demand for resources for the NES assessed, the INPRO assessor should receive information from (potential) technology suppliers (how many primary resources (e.g. tonnes of natural uranium) are needed for each nuclear facility), especially for nuclear reactor(s), e.g. tU per GW(e)·a.

If fissile/fertile materials are not recycled in the NES assessed (e.g. *open* or *once through fuel cycle*), estimation of the total (lifetime) uranium demand for the NES assessed is rather straightforward, namely, just the integration of demand of the primary resource per year over the projected lifetime of the system. Usually, this value should have been already determined in an energy system planning study that is, by definition, a prerequisite for an INPRO assessment (see overview of the INPRO methodology[5]).

If resources are (to be) recycled within the NES assessed (e.g. an NES with a *partly or completely closed fuel cycle*), information is needed on how much fissile/fertile materials are recovered from spent fuel, which could be used as a secondary supply for the NES. Some of this information needed is design specific, e.g. the correlation between the nuclide composition of fresh fuel and spent fuel in a reactor, which depends on core design including the neutron spectrum, fuel arrangement (e.g. seed and blanket arrangements), burnup, etc. To determine the amount of recycled fissile/fertile materials, the results of more sophisticated tools for material flow analysis, such as the Nuclear Fuel Cycle Simulation System (NFCSS) [10] or the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), are necessary; these are available on request from the IAEA.[6]

3.2.1.3. Final assessment of CR1.1: Fissile/fertile material

Global demand and supply of fissile/fertile materials

A detailed study performed within the INPRO project — summarized in Appendix III — came to the conclusion that the currently identified global resources of natural uranium that have a high probability of being provided at reasonably low cost are sufficient to supply fuel to a global NES (consisting of thermal reactors) whose

[5] A publication on this subject is in preparation.

[6] Application of codes such as MESSAGE or NFCSS in analyses is, in principle, not part of an INPRO assessment. However, the INPRO assessor may need the results of such analyses for assessment.

installed capacity could increase to 2500 GW(e) by the end of the century, which is approximately six times greater than the current installed capacity of less than 400 GW(e). The results presented in the Red Book 2011 [13] — summarized in Appendix I — confirm this trend up to the year 2035, and predict that this trend will continue during this century. If the deployment of fast reactors (FRs) is realized in a sufficient amount, which appears likely at the moment in view of developments in a number of technology holder countries worldwide, the currently identified uranium resources (~18×10^6 tU) would be capable of supporting the growth of a global NES with a capacity that is 12 times larger than that of today at the end of the century, i.e. with a capacity of 5000 GW(e). Thus, the balance of global demand and supply of natural uranium has been confirmed until the end of the century in this INPRO study.

INPRO assessors are asked to study the full reports summarized in Appendices I and III, familiarize themselves with the results, and document the main conclusions thereof in the final assessment report. It is also recommended that they contact the IAEA INPRO section, which has an ongoing project on global nuclear energy scenarios. If new studies on this issue become available, they should also be taken into account by the INPRO assessors.

National (regional) demand and supply of fissile/fertile materials

As the global resources of uranium have been found to be sufficient, it can also be concluded that each national NES will have access to sufficient uranium, as long as a global free market for natural uranium supply (and/or nuclear fuel) prevails. National or regional assessments could then be performed to understand how the country, in its national nuclear power programme, could benefit from its own domestic resources and how regional cooperation could potentially be fostered (see the discussion at the beginning of Section 3.2). For this purpose, it is recommended that the INPRO assessor determine the uranium resources necessary for the national (regional) NES assessed using one of the tools available from the IAEA (MESSAGE, NFCSS and Dynamic Energy System — Atomic Energy (DESAE)). To confirm the availability of the required resources, the assessor should take existing national (regional) resources into account.

3.2.2. Criterion CR1.2: Non-renewable materials

Indicator IN1.2: Quantity, $Q_i(t)$*, of material type i available for use in the NES at time* t.

Acceptance limit AL1.2: $Q_j(t) > D_j(t)$*, quantity available for NES,* $Q_j(t)$*, should be bigger than quantity needed,* $D_j(t)$*, for any* $t < 100$ *years.*

In CR1.2, all non-renewable materials (other than fissile and fertile materials) are to be considered that must be continuously available to construct, operate and decommission an NES. As has already been mentioned at the beginning of Section 3.2, a global market exists for non-renewable materials other than fissile and fertile materials, and it is the assessment on a global scale that could prove ultimate compliance with the ALs for IN1.2. However, national and regional assessments also make sense and the more so because it may be much easier for a country to benefit from supplying its domestic non-renewable resources other than fissile and fertile materials for domestic construction of a foreign designed nuclear power plant. Countries may pursue this goal, even at the early stages of their nuclear energy programmes, and turnkey contracts for nuclear power plant construction may have up to 60–70% of the construction costs in domestic materials and labour. Any domestic materials should, of course, meet the reactor grade requirements of a nuclear power plant design. Assessment on the domestic and, potentially, regional scale may, therefore, help define potential benefits from indigenous resource use and foster mutually beneficial cooperation within a region; however, by itself, assessment on the domestic scale will not be sufficient to prove that the ALs for IN1.2 are met.

The assessment of criterion CR1.2 should be performed by comparing the NES demand to global and national (regional) demand, and to available resources, also global and national (regional). Information on metal resources can be obtained from Ref. [14].

Appendix II summarizes the results of a generic study [15] that could be used for assessment of this criterion. This study, performed by the OECD/NEA and published in 2011, is based on life cycle data collected for the Swedish Ringhals plant that includes light water cooled reactors (three pressurized water reactors (PWRs) and one boiling water reactor (BWR)) commissioned between 1976 and 1983. In total, about 70 raw materials were evaluated that were needed for construction, used for operation and foreseen for decommissioning of this plant. The conclusion of the study was that even with a tenfold increase of global nuclear capacity by 2085 to 3720 GW(e), in such a global NES consisting exclusively of reactor types that are currently in operation with a once through fuel cycle, there is no shortage of any raw material to be expected until the end of the twenty-first century. The ongoing introduction of evolutionary reactors replacing currently operating reactors, and the foreseen inclusion of innovative reactors in the global NES, does not change this conclusion, although for the latter designs, limited information is currently available because of the early stage of development. It can also be anticipated that many innovative reactors will adopt non-water coolant technologies, resulting in an essentially different nomenclature of materials. Again, insufficient information is available, at the moment, to assess these differences.

In addition to the materials covered in the OECD/NEA study [15], heavy water moderated reactors need several hundred tonnes of heavy water for startup, and could need several tonnes of it each year to replace losses. However, heavy water is abundant in normal water, albeit at a low concentration, and so there is no shortage of this raw material to be expected.

Based on the OECD/NEA study [15], CR1.2 is met for all non-renewable materials (other than fissile and fertile materials) needed in a global NES and assuming a free market prevails also for a national NES. It is recommended that the INPRO assessor searches the public domain for newer studies on this issue.

3.2.3. Criterion CR1.3: Power supply to the nuclear energy system

Indicator IN1.3: $P(t)$ *= power available (from both internal and external sources) for use in the NES at time* t.

Acceptance limit AL1.3: $P(t) \geq P_{NES}(t)$ *for all* $t < 100$ *years, where* $P_{NES}(t)$ *is the power required by the NES at time* t.

An NES will, at any time, require power (electrical or other) for facility operations, facility construction, etc. The indicator $P(t)$ is the power available at time t for use by the NES from all sources, both internal and external to the NES. At any time throughout the life cycle, this power should equal or exceed $P_{NES}(t)$, the power requirement of the NES at time t. At the beginning of the NES life cycle (i.e. during construction), all of the power would need to be available from external sources, while at later times, the source of much or all of the power for the operation of the NES and/or its growth may be internal to the NES.

Thus, to assess CR1.3, the INPRO assessor should, in close cooperation with (potential) suppliers of the NES assessed:

— Determine the NES requirement of power (i.e. electricity) from outside during construction/operation/decommissioning, and when it would be required;
— Verify the availability of the required non-nuclear (e.g. fossil fuel, hydro) power from outside and corresponding resources during the lifetime of the NES.

Regarding power supplied to NESs based on fossil fuel energy, several references exist on fossil fuel resources that can be used for the assessment, e.g. Refs [16, 17]. Scenarios for fossil fuel exploitation and use are described in these two references when discussing uranium scenarios.

3.2.4. Criterion CR1.4: End use of uranium

Indicator IN1.4: U_{eu} *= end use (net) energy (GW·h) delivered by the NES per tonne of uranium mined.*

Acceptance limit AL1.4: $U_{eu} > U_0$; U_0 *= maximum end use achievable for an existing NES with a once through nuclear fuel cycle.*

CR1.4 should be addressed by integrating the sum of all energy uses throughout the lifetime of all components of the NES to determine the net (electric) energy generated by the NES assessed per tonne of natural uranium used, i.e. the value of U_{eu}.

The calculated values for uranium use of the NES assessed per energy delivered should be compared with the uranium use efficiency of an existing NES with an open (once through) fuel cycle, i.e. the value of U_0.

There is a generic study available to the INPRO assessor defining U_0, namely, the study documented in Ref. [18]. This study determined, for current (around the year 2000) nuclear fuel cycles associated with light water reactors (LWRs) in western Europe, a net electricity delivery (to grid) per unit of uranium ore consumption in the range 42–50 GW·h/t natural uranium. An average value of 44 GW·h/t natural uranium can be assumed [19] for electricity delivery of NESs in Europe. The range of end uses depends on the assumed burnup, the average enrichment of fresh fuel and the source of enrichment services (centrifuge enrichment uses about 60 times less energy than diffusion per separative work unit).

Reference [4] presents a simplified calculation of the end use of natural uranium in an NES with an open (once through) fuel cycle. It determined a value for U_0 of 40.5 GW·h per tonne of natural uranium used.

Thus, criterion CR1.4 is met, if the net energy delivered by the NES assessed per unit of uranium used is higher than the value of an existing NES consisting of an LWR with an open fuel cycle.

3.2.5. Criterion CR1.5: End use of thorium

Indicator IN1.5: Th_{eu} = end use (net) energy (GW·h) delivered by the NES per tonne of thorium mined.

Acceptance limit AL1.5: $Th_{eu} > Th_0$; Th_0 = maximum end use achievable with a current operating thorium cycle.

The calculated end use values for an NES designed to use a thorium ($^{232}Th/^{233}U$) fuel cycle should be compared with the thorium use efficiency of a current thorium cycle confirming the increased efficiency of the NES to be installed (developed). However, this criterion could not be assessed by a nuclear technology user at the time that this publication was written, because as of 2014, there was no NES operating on a thorium cycle. Therefore, this criterion is thought to be considered exclusively by nuclear technology developers.

3.2.6. Criterion CR1.6: End use of other non-renewable resources

Indicator IN1.6: C_i *= end use (net) energy delivered by the NES per tonne of limited non-renewable resource consumed.*

Acceptance limit AL1.6: $C_i > C_0$; C_0 *to be determined on a case specific basis.*

Cumulative consumption of non-renewable resources (other than fissile and fertile materials) per unit of net energy delivered (i.e. material use rate efficiency) should be compared with the results for an existing NES with an open fuel cycle.

There is a generic study available for the INPRO assessor that defines C_0 for some non-renewable materials, i.e. the study documented in Ref. [18]. This study determined, for current (around year 2000) nuclear fuel cycles associated with LWRs in western Europe, the consumption of copper, iron and gravel (the latter as a measure of concrete use) as reported in Table 4 (more data on specific reactor type and country as well as on other resources are available in Ref. [20]). The ranges of consumption depend upon the assumed key parameters for the different fuel cycles in the country and the type of LWR. Not surprisingly, the study shows that the highest material use throughout the life cycle is calculated for the construction phase of a nuclear power plant.

To produce fuel assemblies for operating and evolutionary water cooled reactors, various zirconium alloys are currently used. One of the reasons for using zirconium alloys as fuel claddings is that zirconium has a low cross-section of neutron capture, which is necessary for efficient fuel utilization. However, zircon sand, which is the main source of zirconium, usually contains an admixture of hafnium in various quantities. Hafnium has an extremely high neutron capture cross-section, and needs to be separated from the zirconium used for nuclear fuel fabrication, which means that the cost of nuclear grade (refined) zirconium may depend on the amount of hafnium in the deposits.

TABLE 4. EXAMPLES OF CUMULATIVE RESOURCE CONSUMPTION (IN YEAR 2000) FOR EUROPEAN LIGHT WATER REACTOR ENERGY CHAINS [18, 19]

Material	Minimum (GW·h/t)	Maximum (GW·h/t)
Copper	1.68×10^2	2.07×10^2
Iron	2.93	3.66
Gravel	2.44×10^{-1}	3.06×10^{-1}

A study performed under the aegis of INPRO [21] mentioned the zirconium availability issue in the framework of NES sustainability assessment. An operating reactor of 1 GW installed capacity annually consumes ~10 t of zirconium [22]. Countries that plan on increasing their nuclear power capacity will substantially increase zirconium consumption, e.g. China expects the demand for zirconium by its nuclear power industry to exceed 8000 t/a during the next decade.

An estimation of zirconium supply needed to utilize the total global amount of natural uranium resources of ~20×10^6 tU in PWR reactors can be performed as follows. The share of UO_2 in a typical PWR fuel assembly amounts to approximately 0.7 of the total assembly weight [23]. The rest of the assembly weight (0.3 of the total) comprises mainly fuel rod claddings, assembly nozzles and spacers. Conservatively assuming that 3 kg of zirconium is necessary to utilize 7 kg of UO_2 and that uranium enrichment in the fuel is 4%, it can be approximately estimated that 1.2×10^6 t of zirconium would be necessary to use 20×10^6 tU.

As the world resources of zircon exceeded 60×10^6 t, according to the US Geological Survey in 2013 [14], it can be assumed that there will be no shortage of this material. However, as is summarized in the OECD/NEA study [15], zircon sand is produced as a by-product of titanium production, and zircon supply is heavily dependent on titanium demand. Supply is tight and oriented towards applications in the ceramics industry, because this sector covers over 50% of the total production. Annual global production of zirconium amounts to approximately 1.5×10^6 t (1.62×10^6 t in 2011 and 1.42×10^6 t in 2012 [14]). At the current consumption rate, world resources of zirconium will last less than 40 years. New explorations of zirconium deposits are expected to enlarge zirconium reserves.

For other important non-renewable materials needed for NESs, a preliminary study published by the OECD/NEA [15] can be used.

Thus, the INPRO assessor should select the key materials determined during the assessment of criterion CR1.2, determine their accumulated consumption in the NES assessed and compare them to the consumption in an existing NES.

Criterion CR1.5 is met if the consumption of non-renewable materials in the NES assessed per energy delivered is lower than the corresponding values for an existing NES. In the case when a given resource is not used in an existing NES, the assessor's judgment should be based on the result of global production and consumption analysis.

3.3. USER REQUIREMENT UR2: ADEQUATE NET ENERGY OUTPUT

User requirement UR2: The energy output of the NES should exceed the energy required to implement, operate and decommission the NES within an acceptably short period.

The net energy output of an NES is the usable energy produced by the system over and above the energy required to install, operate and decommission the system, over its intended life cycle. The net energy balance (output minus input) should turn to a positive value in an acceptably short period after startup; obviously, the shorter the better.

The INPRO methodology has defined one criterion for UR2, as shown in Table 5.

TABLE 5. CRITERION CR2.1 FOR USER REQUIREMENT UR2

User requirement (UR)	Criterion (CR)	Indicator (IN) and acceptance limit (AL)
UR2: Adequate net energy output: The energy output of the NES should exceed the energy required to implement, operate and decommission the NES within an acceptably short period	CR2.1: Amortization time	IN2.1: T_{EQ} = time required to match the total energy input into the NES with energy output (years) AL2.1: $T_{EQ} << T_L$; T_L = intended lifetime of NES

3.3.1. Criterion CR2.1: Amortization time

Indicator IN2.1: T_{EQ} *= time required to match the total energy input into the NES with energy output (years).*

Acceptance limit AL2.1: $T_{EQ} << T_L$; T_L *= intended lifetime of NES.*

CR2.1 requires that the T_{EQ} of an NES is adequately short, i.e. the time needed to generate the amount of power that is needed to install, operate and decommission the NES should be much shorter than the lifetime T_L of the system. The value of T_{EQ} depends on the purpose of the NES, e.g. whether the NES is to be used for power generation or if it is to be used as an MA burner for high level waste reduction. In the first case, the value of T_{EQ} can be assumed to be lower or even much lower than for the second, because the second system should be designed to optimize MA burning, not for energy conversion.

There is one generic study available to the INPRO assessor that defines the T_{EQ} of a current NES, namely, the life cycle assessment study documented in Ref. [18]. This study determined, for a current (year 2000) PWR operational in western Europe using uranium enriched by a centrifuge only and a partly closed fuel cycle (mono plutonium recycling by reprocessing of uranium spent fuel), an approximate T_{EQ} of 5 months for a 40 year operational lifetime, with all energy requirements throughout the life cycle included. This value was not calculated by the software used in ecoinvent [24], but indirectly through the total (cumulative) waste energy divided by the direct electricity output from the power plant. A reference efficiency of 35% for the conversion of thermal energy to electricity was used to express the total energy requirements in electricity equivalent units [18]. The average value of T_{EQ} calculated for western European LWRs was ~17 months, owing to the relatively high share of enrichment by diffusion in 2000, which was assumed to be used for approximately 65% of the total supply of enriched uranium.

Another generic study on NESs completed by the World Nuclear Association (WNA) in 2003 [25] shows that the total amount of power used by a typical NES for construction, operation and decommissioning was far less than the power generated (by a factor of 20 or more). For an NES to be installed during the twenty-first century, it is expected that the ratio will be even higher because of more efficient fuel utilization, advanced designs and the use of improved materials and construction techniques.

Thus, criterion CR2.1 is met for the NES assessed if its T_{EQ} is adequately short, i.e. much shorter than the lifetime of the system and shorter than for an existing NES. For example, in the case of an NES (using a PWR with mono recycling of plutonium and centrifuges for enrichment) designed for power generation, T_{EQ} should be less than 5 months.

Instead of using the EPBT, the INPRO assessor could use the energy profit ratio (EPR) to evaluate this criterion. The EPR is the ratio of total energy output to input, whereas the EPBT is based on the difference of energy output and energy input.

Appendix I

FISSILE/FERTILE MATERIALS: GLOBAL SUPPLY AND DEMAND

This appendix presents a summary of the information generated in selected studies on global demand and supply of uranium during the twenty-first century.

First, the global uranium supply documented in the Red Book 2011 [13] — a joint report by the OECD/NEA and the IAEA published in 2012 — will be presented in some detail, covering fissile/fertile materials such as uranium and thorium resources, uranium exploration and uranium production. This information will be compared to the global uranium demand projected until 2035, and the supply and demand relationship will be discussed.

Second, the main results of an IAEA report [11] analysing uranium supply to 2050 will be briefly presented.

Third, an OECD study [26] will be briefly described that focuses on the sustainability of nuclear fuel cycles.

Finally, a brief summary of a WNA study [27] on the global nuclear fuel market is presented.

I.1 GLOBAL URANIUM SUPPLY AND DEMAND DEFINED IN THE RED BOOK

The Red Book 2011 [13] defines categories of uranium resources that could be mined (also called primary resources) based on confidence levels and costs to mine.

I.1.1. Definition of resource categories

The estimated uranium resources reported in the Red Book 2011 [13] are classified on the basis of confidence levels in the quantities reported, and further separated into categories based on the cost of production.

Two broad classes of uranium resources to be mined are distinguished: conventional and unconventional. *Conventional resources* are those that have an established history of production where uranium is a primary product, co-product or an important by-product (e.g. from the mining of copper and gold). Very low grade resources or those from which uranium is only recoverable as a minor by-product are considered *unconventional resources.*

Conventional resources are further divided, according to different confidence levels of occurrence, into four categories: *reasonable assured resources* (RARs), *inferred resources* (IRs), *prognosticated resources* (PRs) and *speculative resources* (SRs). RARs and IRs together are called *identified resources* and refer to uranium deposits delineated by sufficient direct measurement to conduct feasibility or prefeasibility studies. PRs and SRs together are called *undiscovered resources* and refer to uranium resources that are expected to exist based on geological knowledge of previously discovered deposits and regional geological mapping.

Examples of unconventional resources of uranium are phosphate rocks, non-ferrous ores, carbonatite, black shale and lignite. Additionally, sea water contains uranium, albeit at a rather low concentration of 3–4 parts per billion (ppb).

There is also a classification scheme developed by the United Nations Economic Commission for Europe called the United Nations Framework Classification for Fossil Energy and Mineral Resources 2009 (UNFC-2009). UNFC-2009 is a generic principle based system in which quantities are classified on the basis of the three fundamental criteria of economic and social viability (E), field project status and feasibility (F) and geological knowledge (G), using a numerical coding system. Combinations of these criteria create a three dimensional system [28]. UNFC-2009 is a project based system that applies to all fossil fuel energy and mineral reserves and resources. It has been designed to meet, to the extent possible, the needs of applications pertaining to energy and mineral studies, resource management functions, corporate business processes and financial reporting standards. A bridging document between the OECD/NEA–IAEA 'Red Book' uranium classification and UNFC-2009 was published in late 2014 [29].

I.1.2. Definition of cost categories

The Red Book 2011 [13] defines four categories of costs in US dollars of uranium recovered at the ore processing plant: <US $40/kgU, <US $80/kgU, <US $130/kgU and <US $260/kgU (kgU = kilograms of uranium).

In the following sections, the global resources of uranium and thorium are presented as defined in the Red Book 2011 [13].

I.1.3. Global conventional resources of uranium

Table 6 shows the conventional resources, as of 2011, for the four categories, namely RARs, IRs, PRs and SRs, in the four cost categories defined above. As mentioned previously, the sum of RARs and IRs is also called *identified* resources.

TABLE 6. CONVENTIONAL RESOURCES OF URANIUM IN 2011 ($\times 10^3$ tU) [13]

Type of global uranium resources	Cost category			
	<US $40/kgU	<US $80/kgU	<US $130/kgU	<US $260/kgU
RAR	493	2 014	3 455	4 378
IR	187	1 063	1 871	2 717
PR	—	1 624	2 698	2 841
SR	—	—	3 543	7 595*
Total	680	4 701	11 567	17 531

Note: IR: inferred resource; PR: prognosticated resource; RAR: reasonable assured resource; SR: speculative resource; tU: tonnes of natural uranium.

* Includes resources with unassigned cost ranges.

Thus, as of 2011, the total global *conventional* resources of uranium that can be mined with production costs below US $260/kgU were reported to be ~18×10^6 t and the *identified* resources were ~7×10^6 tU. The Red Book 2011 [13] further lists these resources separately for individual countries and different production methods.

I.1.4. Global unconventional global resources of uranium

As stated above, unconventional resources of uranium are contained in phosphate rocks, non-ferrous ores, carbonatite, black shales and lignite. As of 2011, the reported unconventional global resources in these geological formations were 7.3×10^6–8.0×10^6 tU, mainly in Morocco. However, not included in this value are the large uranium resources associated with the Chattanooga (USA) and Ronneburg (Germany) black shales, which together contain a total of 4.2×10^6 tU. Total unconventional uranium resources (primarily in phosphates) are estimated at up to 22×10^6 tU. Costs to recover these resources have a significant uncertainty and cover a wide range of <US $40/kgU up to >US $260/kgU.

Sea water is also regarded as a possible source of uranium due to its large amount of contained uranium, i.e. over 4×10^9 tU in total, but at a low concentration of ~3 ppb. However, the costs of extracting uranium from sea water are defined with a high uncertainty, and are estimated to be in the range US $200/kgU to US $700/kgU.

I.1.5. Secondary supply of fissile material

Table 6 listed the amount of conventional resources of uranium and Section I.1.4 gave the unconventional resources of uranium. These categories of fissile and fertile materials are called *primary resources.*

In addition to primary resources, there is also *secondary supply* of fissile material based on mined and processed uranium as discussed below.

Depleted uranium

The global amount of depleted uranium from enrichment of natural uranium was estimated by the Red Book 2011 [13] to be ~1.6×10^6 t. This corresponds to an equivalent amount of natural uranium of ~450×10^3 tU.

Inventories of uranium

The Red Book 2011 [13] estimated that 560×10^3 t of natural uranium and ~34×10^3 t of low enriched uranium (LEU) are stored in commercial (utilities) and national inventories.

Highly enriched uranium

Several programmes have been performed by the Russian Federation and the USA to downgrade HEU (weapons grade uranium) to LEU for commercial power (and research) reactors. In one programme, ~500 t of HEU from the Russian Federation are to be converted into 14×10^3 t of LEU in the USA. Another programme will convert ~300 t of HEU from the USA into ~8.4×10^3 t LEU available for commercial reactors.

Reprocessed uranium

Owing to the rather high costs of production of fuel with REPU, there is currently no significant activity in this area other than in France, with an annual generation of ~1×10^3 t. The amount of stored REPU is not reported in the Red Book 2011 [13].

Plutonium from reprocessing of spent fuel

France has a production of mixed oxide (MOX) fuel of ~200 t/a. Japan plans to install a comparable capacity of MOX fuel production.

Plutonium from military programmes

An amount of ~70 t of military plutonium is planned to be converted into MOX fuel. The 70 t of plutonium corresponds to an equivalent amount of natural uranium of ~15×10^3 t.

Spent nuclear fuel

Approximately 240×10^3 t of spent nuclear fuel (SNF) has currently been accumulated worldwide, and ~10×10^3 t are added every year [30] by the current size of the reactor fleet of ~370 GW(e) installed capacity. This SNF contains more than 98% fissile/fertile materials that can be recycled into nuclear fuel.

Summarizing the information on secondary supply above, the amount of fissile material available from military programme conversion of weapons grade material is expected to decrease after 2013. However, depleted uranium and SNF are potential resources of fissile material that could satisfy the global nuclear fuel demand for several decades in a thermal reactor fleet and practically infinitely in the case of an FR fleet.

I.1.6. Resources of thorium

Like uranium, thorium can be used as a nuclear fuel. Although it is not fissile itself, when loaded into a nuclear reactor, ^{232}Th absorbs neutrons to produce ^{233}U, which is fissile (and long lived). Much of the ^{233}U will then fission in the reactor. The used fuel can then be unloaded from the reactor, and the remaining ^{233}U can be chemically separated from the thorium and used as fuel for another reactor.

Thorium's global abundance is between three and five times that of uranium. It is found in four distinct types of thorium deposits. In decreasing order of importance, these are carbonatite hosted, placer, vein type and alkaline rock hosted. As of 2011, the total amount of global thorium resources was in the range 6.7×10^6–7.6×10^6 t.

A comprehensive IAEA report on the role of thorium to supplement fuel cycles of future NESs is available (see Ref. [31]).

I.1.7. Global exploration and production of uranium

In 2010, the global expenditures on exploration and mine development totalled over US $2 billion. Generally, higher prices for uranium since 2003, compared to the preceding two decades, have stimulated increased explorations worldwide (see Figs 2 and 3).

Global production of uranium amounted to 54 670 tU in 2010. In situ leaching mining accounted for 39%, underground mining for 32%, open/pit mining for 23%, and co-product and by-product recovery from copper and gold operations for 6% of the total global production in 2010. The world uranium production capability[7] using identified resources (RARs and IRs) recoverable at costs of up to US $130/kgU is expected to increase from 73 305 tU/a to 109 460 tU/a in 2035.

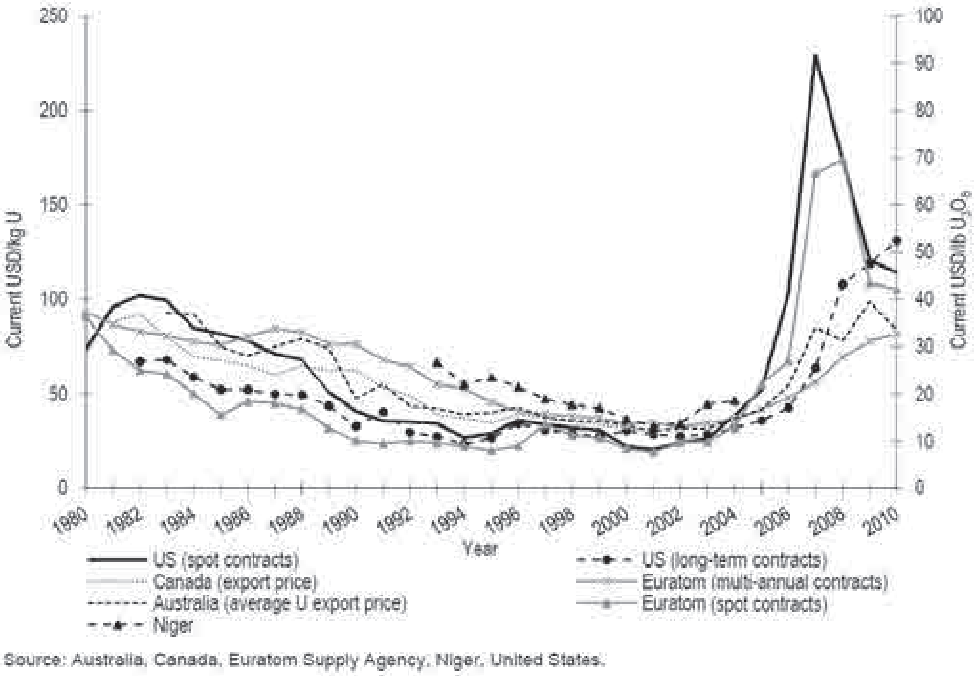

FIG. 2. Uranium prices in the time period 1980–2010 [13].

[7] Production capability is not production. Historically, production has never reached more than ~90% of production capability.

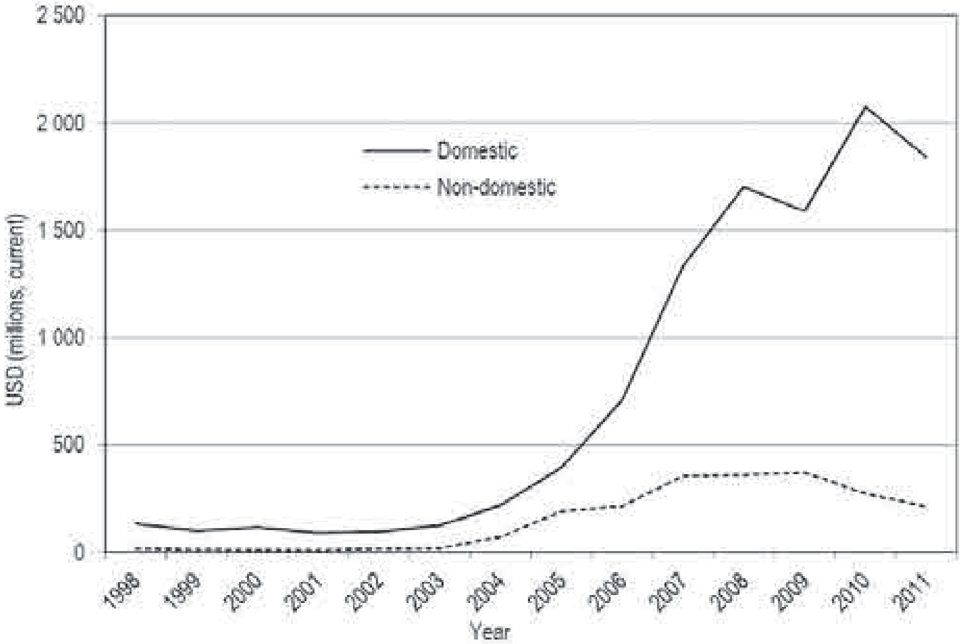

FIG. 3. Trends in uranium exploration and development expenditures 1998–2011 [13].

I.1.8. Global demand for uranium defined in the Red Book

At the beginning of 2011, there were 440 reactors in operation globally, with an electricity generating capacity of ~375 GW(e) and a global demand for uranium of 63 875 tU/a. The corresponding world uranium production of 54 670 tU met ~85% of this world reactor demand. The remainder of the supply came from uranium already mined, i.e. the so called *secondary sources* (see Section I.1.5 above), and included excess governmental and commercial inventories, LEU produced from nuclear weapons, re-enrichment of depleted uranium tails and MOX fuel from spent fuel reprocessing. This secondary supply is expected to decline somewhat after 2013.

The future demand for uranium in the Red Book 2011 [13] is based on two forecasts for the year 2035: a low case with an increase of global nuclear capacity from 375 GW(e) up to 540 GW(e), and a high case with an increase up to 746 GW(e). World reactor related uranium production requirements by the year 2035 (assuming an enrichment tails assay of 0.30%) are projected to increase to a total of between 97 645 tU/a in the low case and 136 385 tU/a in the high case, representing increases of ~50% and ~110%, respectively, compared to 2011 production requirements.

Accumulated total uranium requirements are estimated to be ~2.5×10^6 tU and ~2×10^6 tU by 2035, for the high and low cases, respectively. This means that only 35% of identified resources (7×10^6 tU, RARs plus IRs) would be consumed by 2035 in the high case, and only 29% in the low case.

I.1.9. Balance of global uranium demand and supply in the Red Book

Figure 4 shows the historic demand and supply of uranium starting from 1945 until 2011, and indicates that at the start of nuclear power until about 1991, natural uranium production surpassed uranium consumption (demand). This enabled buildup of national and commercial inventories of natural uranium that are part of the so called secondary uranium supply. The deficit between production and demand after 1991 was mitigated by the drawdown of these inventories and other secondary uranium supplies, such as conversion of HEU from military programmes into LEU (see Section I.1.5).

FIG. 4. Historic demand and supply of uranium [13].

Figure 5 shows the predicted development of annual demand and supply of uranium from 2005 until the year 2035 for the two scenarios of demand (high and low) presented in Section I.8.

Although Fig. 5 seems to suggest an oversupplied uranium market in the near term, i.e. until 2020 and 2025, for the high and low demand cases, respectively, experience shows that this is not likely to happen because production capability is not actual production.

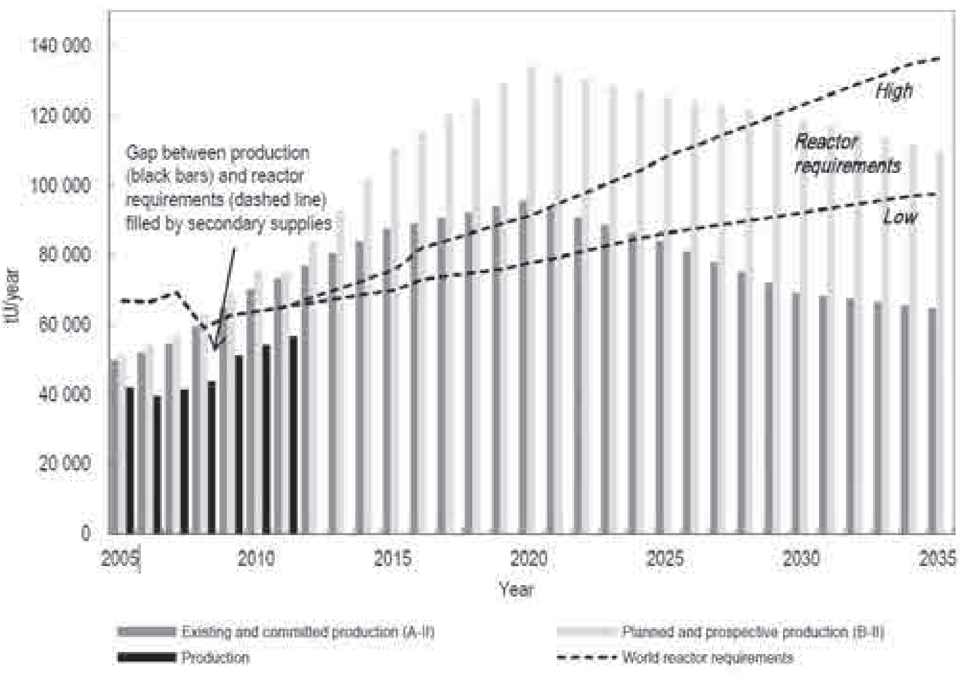

FIG. 5. Projected annual world uranium production capability to 2035 compared with projected world uranium demand [13].

The gap between uranium production (black bars) and demand for reactor operation (dashed lines) from 2005 to 2010 has been met by drawing down secondary supply of uranium. This will also be the case in a reduced form for the near future.

Figure 5 also indicates that timely investment in uranium production facilities will be necessary, taking account of the long lead times to turn resources into production.

I.1.10. Conclusions based on the information in the Red Book

There exist sufficient uranium resources to support continued global use of nuclear power and for significant growth in nuclear capacity up to 2035 and beyond. In the high growth scenario (746 GW(e)), only 2.5×10^6 tU, i.e. 35% of the identified resources (RARs plus IRs), of the 7×10^6 tU would be consumed by 2035, and only 2×10^6 tU, i.e. 29%, in the low growth scenario (540 GW(e)).

The known, conventional resources (RARs plus IRs plus PRs plus SRs) of ~18×10^6 tU would be sufficient to continuously supply the current necessary annual amount of uranium ~70×10^3 tU/a of the current global NES for about 300 years.

The total resource base reported in 2011 — conventional plus unconventional resources of ~40×10^6 tU — is more than adequate to meet the projected growth requirements to 2035 in the low and high case scenarios. However, timely investment is necessary to convert reported uranium resources (phosphates) into production facilities.

If uranium resources in sea water — estimated to be more than 4×10^9 tU — become available, it would lead to practically inexhaustible resources.

History (Fig. 2) has also shown that as soon as uranium prices start to increase (because of predicted shortages), uranium exploration will also increase (Fig. 3), and therefore enough uranium production will be available in time for the operation of all nuclear reactors.

I.2. ANALYSIS OF URANIUM DEMAND AND SUPPLY TO 2050 BY THE IAEA

The objective of the IAEA report Analysis of Uranium Supply to 2050 [11] (first published in 2001 and being updated in 2015 to cover a period up to ~2060) was to assess the adequacy of uranium resources to satisfy market based production demand and to characterize the level of confidence that can be placed in the projected supply. The study considered the uranium resources reported in the 2000 edition of the Red Book [32] and the International Institute for Applied Systems Analysis (IIASA)/World Energy Council (WEC) scenarios from Ref. [33] for evaluation of uranium demand and supply.

I.2.1. Projected growth of the global nuclear energy system to 2050

Three demand cases (low, middle and high) were considered in Ref. [11], covering a broad range of assumptions as to worldwide economic growth and related growth in energy and nuclear power up to the year 2050. In the low case scenario, the global installed nuclear capacity reached 333 GW(e), in the medium case, it reached 1132 GW(e), and in the high case, it reached 1805 GW(e), by 2050.

I.2.2. Projected demand for uranium by the global nuclear energy system to 2050

The cumulative uranium requirements between 2000 and 2050 for the three scenarios were projected as 3.39×10^6 tU, 5.39×10^6 tU and 7.58×10^6 tU, respectively, for the low (corresponding to IIASA/WEC case C1 in Ref. [33]), middle (case C2 in Ref. [33]) and high (case A3 in Ref. [33]) demand cases.

I.2.3. Resources of uranium

The study (see Ref. [11]) used detailed information on primary and secondary supplies documented in the Red Book 2000 [32] plus data based on evaluations carried out by the authors of the study.

Figure 6 shows how different categories of uranium resources known in 2000 could be used to satisfy the demand for annual production of uranium until 2050.

The model used in Ref. [11] to project production and resource adequacy presents a number of scenarios including alternatives as to how the industry could evolve depending on specific conditions. According to the study:

> "The adequacy of resources to meet demand is measured in two ways. The first measure is a direct comparison of resources at different confidence levels with market based production requirements. The second measure takes into account the fact that not all resources will be utilized within the study period by comparing projected production with market-based requirements" [11].

I.2.4. Conclusions from the IAEA study to 2050

One conclusion of the study [11] was that uranium production from high confidence known resources was projected to be adequate to meet all requirements in the low demand case until 2050.

For the middle demand case, relatively high confidence known resources fell somewhat short of market based production requirements from 2041 on. Conversely, if PRs were available, resources would exceed requirements. However, if timing when production centres would be cost justified and the size of their resource base was taken into account, the study predicted a shortfall of approximately 0.8×10^6 tU. Considering prices, lower cost (<US $130/kgU) conventional resources were not available to meet the uranium demand in the middle and high demand cases, even when EAR-II (estimated additional resources as part of undiscovered conventional resources) were taken into account. However, if very high cost (>US $130/kgU) conventional resources were taken into account, together with unconventional resources, sufficient uranium supply may meet both the middle and high demand cases, as the lower cost known resources would become exhausted. In addition, SRs may be explored, which may include low cost resources. A condition is that significant and timely exploration of these SRs would be undertaken (typically between 8 and 10 years are necessary from discovery to start of production, and 5 or more years must be added for exploration and discovery and for the potential of completing even longer and more expensive environmental reviews [34]).

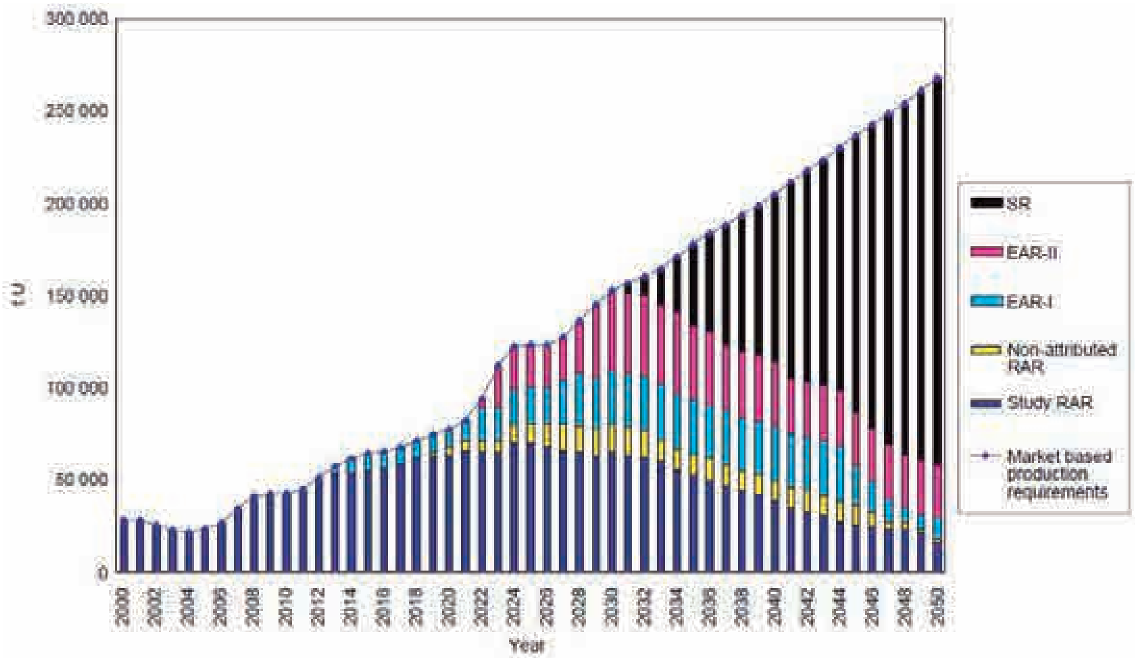

FIG. 6. Resource contribution by confidence level [11]. EAR — estimated additional resources; RAR — reasonable assured resource; SR — speculative resource.

Therefore, in a second conclusion, both the middle and high demand cases could be supplied by either rather high cost conventional and unconventional resources, or by new lower cost conventional resource discoveries made from SRs, although overconfidence should be avoided in yet undiscovered resources.

I.3. TRENDS TOWARDS SUSTAINABILITY IN THE NUCLEAR FUEL CYCLE

The OECD/NEA study published in 2011 [26] assessed trends in the nuclear fuel cycle over the past 10 years, for the next 10 years and for the long term future. It focused on considerations of sustainability according to the INPRO methodology covering aspects of environmental stressors, resource utilization, waste management, infrastructure, proliferation resistance and physical protection, safety and economics.

In 2011, there were two types of commercial fuel cycles in use for management of irradiated (or spent) nuclear fuel: the once through (or open) cycle, where the fresh fuel is used for one cycle in the reactor and then treated as a waste to be disposed of, and a partially closed cycle where the spent fuel is reprocessed to recover uranium and plutonium for recycling in fresh MOX fuel.

Based on the 2009 edition of the Red Book [35], uranium resources are expected to be sufficient for at least another 100 years of supply (at 2008 reactor requirement levels), and production is expected to be more than adequate to meet demand in the near term, provided that existing and committed plans of capacity expansion are achieved in a timely manner. However, starting around 2000, uranium prices have generally increased and become more volatile. The need for timely availability of natural uranium has become more important in terms of security of supply for utilities and governments, as exemplified by the progressively longer term supply contracts, the buildup of strategic stockpiles and the tendency of reactor suppliers to move into uranium mining in order to secure supply and to hedge against the rising prices of natural uranium. These altered market conditions require significant timely investment into exploration and building of uranium production facilities.

These conditions of the uranium market have led to continuous evolution of the fuel cycle technologies and strategies driven mostly by the industry to optimize design and operation of reactors and their associated fuel cycle facilities.

The trends regarding uranium resource utilization are either neutral or show improvements, especially for the next decade. However, longer fuel cycles lead to less efficient resource utilization, and increased plant availability increases the annual demand for uranium produced per GW(e) installed. The ongoing depletion of secondary supply has led to a higher demand for primary resources, causing higher uranium prices, which, in turn, have stimulated new exploration and commissioning activities. The study emphasizes that an increased use of MOX and REPU fuel would significantly reduce the demand for new uranium resources to be developed.

Higher uranium and conversion prices have been detrimental to the economics of nuclear power, but the overall effect on the competiveness of nuclear energy has been small because fuel costs represent only a small proportion of the overall electricity generating costs.

I.4. GLOBAL NUCLEAR FUEL MARKET: SUPPLY AND DEMAND 2013–2030

In 2013, the WNA published a report [27] on the expected development of the global nuclear fuel market to 2030.

The study emphasized the complexity of a typical nuclear fuel cycle (see Fig. 7).

An important feature of the nuclear fuel cycle is the relatively low cost of transportation of uranium due to its high energy density. Thus, mining, enrichment, fuel fabrication and use in a reactor is being carried out economically in different countries.

Fuel costs in nuclear power have been a relatively minor element in total production costs compared to the costs of fossil fuel in generating electricity. Nuclear fuel costs are usually below 20% of the total production costs, whereas fossil fuel costs can be up to 80% of the total.

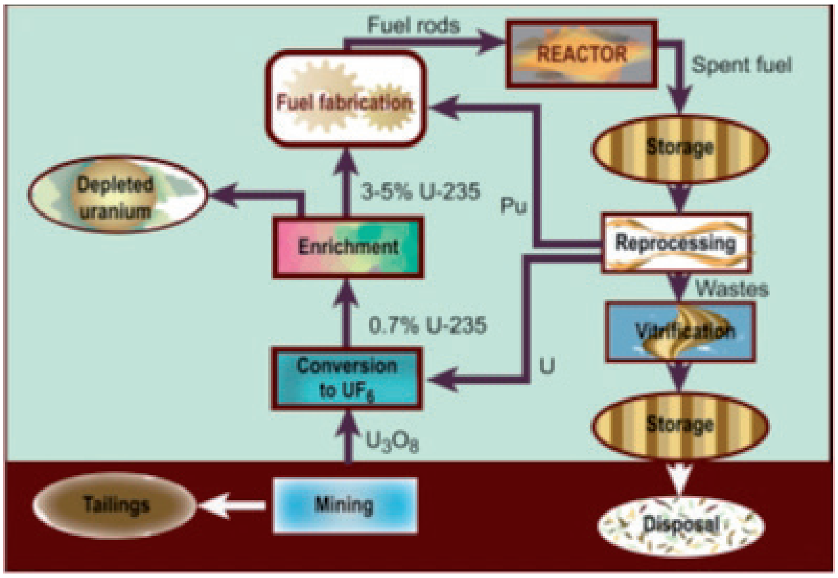

FIG. 7. Nuclear fuel cycle of a thermal reactor with recycling of uranium and plutonium [27].

Production of uranium from primary resources has recently not covered more than 60–80% of the annual demand. The remaining amount of uranium has been supplied by secondary uranium sources, e.g. drawdown of inventories, down blending of military uranium, etc. The contribution of secondary supply will continue over the entire period to 2030.

The WNA study considered three scenarios for growth of global nuclear power to 2030 (see Fig. 8): lower, reference and upper.

The global nuclear capacity was assumed to reach 574 GW(e) in the reference scenario, to reach 700 GW(e) in the upper scenario and to remain approximately at the current level of 340 GW(e) in the lower scenario by 2030.

In addition to these global scenarios for every country with an existing or planned nuclear power programme, the predicted growth of national nuclear capacity was documented in the study.

To determine the necessary supply of uranium for the predicted scenarios, several factors of NES operation have to be taken into account. For example, an increase of power plant load factor or reactor cycle length leads to a higher specific demand for natural uranium (tU per GW(e)). A decrease of enrichment tails assay and an increase of fuel burnup results in a lower specific demand. However, in the case of higher burnup, higher enrichment would usually be necessary, which would lead to a higher demand.

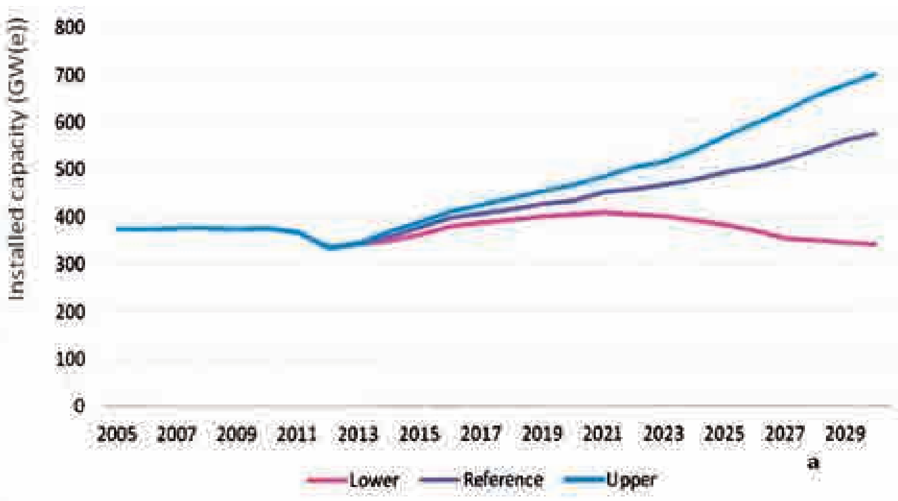

FIG. 8. Scenarios for global nuclear power [27].

The study presents detailed information on secondary sources of uranium available on the market. For example, the amount of spent fuel mostly stored at reactor sites amounts to almost 2×10^5 t (equivalent to ~4×10^5 tU). Depleted uranium has accumulated to over 1.5×10^6 t (by content of ^{235}U, it is equivalent to ~4.2×10^5 tU).

Figure 9 shows the annual production of uranium that is needed to fuel the global reactor fleet in the three scenarios selected. In the reference scenario, an annual production of uranium of 9.7×10^4 tU/a is needed by 2030, in the upper scenario, it is 1.2×10^5 tU/a, and in the lower scenario, it is 5.9×10^4 tU/a. These global figures are based on country specific values for load factors, cycle length, enrichment, burnup, etc. (and also on global assumptions, e.g. global tails assays are 0.22% of ^{235}U).

For defining the available global resources of uranium, the study used the information presented in the Red Book 2011 [13] that defined a total value of identified (RARs plus IRs) uranium resources of 7.1×10^6 tU with production costs lower than US $260/kgU. The Red Book 2011 also defined a world total of ~18×10^6 tU, including less well proven resources termed PRs and SRs.

To estimate the future worldwide production of uranium until 2030, the study differentiated between the current capacity of mines that are already in operation, mines under development for which development decisions have been made, planned mines for which a feasibility study has been completed, and prospective mines that have been publicly announced but which require further commercial analysis. Based on the growth scenarios of nuclear power, three scenarios for the future uranium production (reference, upper and lower) were developed, with different assumptions regarding delays of startup of mines and capacity.

Figure 10 shows the expected global annual production of uranium, combining the information from each country with known uranium resources. In 2030, the expected annual production of uranium reaches values of 6×10^4 tU/a, 5.3×10^4 tU/a and 4.7×10^4 tU/a, according to the upper, reference and lower scenarios, respectively.

Comparing Fig. 10 with Fig. 9 indicates that there are not sufficient supplies expected for the reference and upper scenarios from mining primary uranium resources. This gap could be closed by exploration and commissioning of new mines and use of secondary uranium supplies.

Figure 11 shows the results for expected supply by secondary sources. Again, different assumptions have been made for the availability of secondary sources. In the reference case, secondary supply is expected to decline from 2×10^4 tU/a to 1.5×10^4 tU/a after 2013, reaching a value of ~1.3×10^4 tU/a in 2030; in the upper case, the supply decreases to ~1.7×10^4 tU/a in 2014 and by 2030 remains at the same level; in the lower case, the supply decreases to 1.3×10^4 tU/a after 2013 and reaches a value of ~1×10^4 tU/a in 2030.

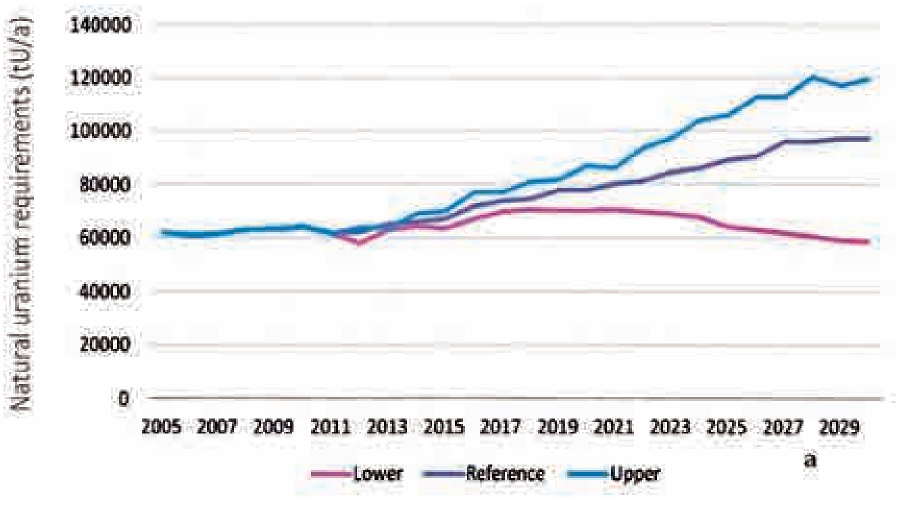

FIG. 9. Expected annual uranium requirements for the three selected scenarios with different growth rates of nuclear power [27].

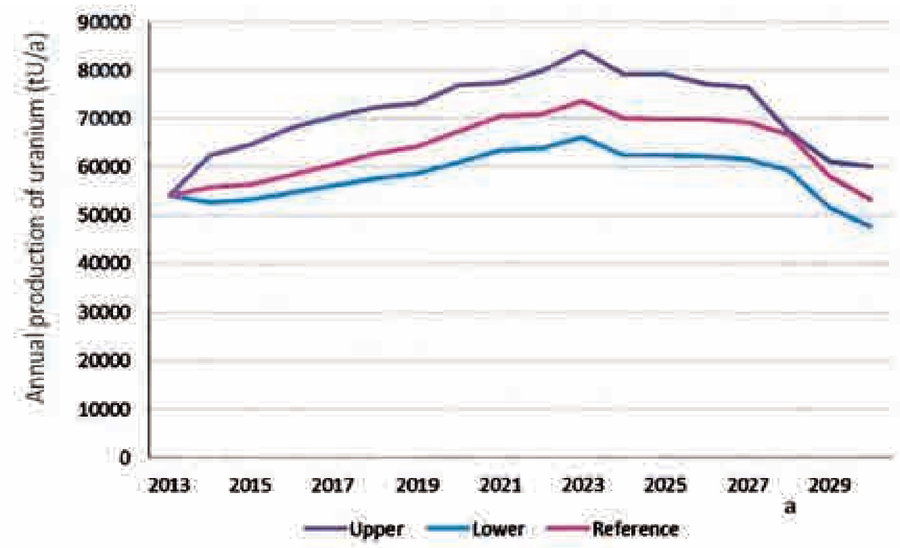

FIG. 10. Expected annual production of uranium from primary resources [27].

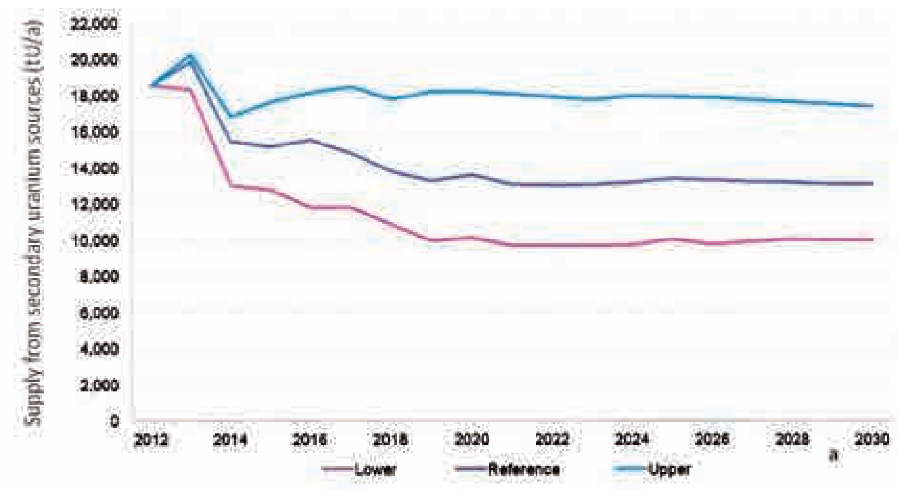

FIG. 11. Expected global supply from secondary uranium sources based on different assumptions [27].

A comparison between predicted total annual supply of uranium by primary resources and secondary sources with the demand for uranium is presented in Fig. 12 for the reference scenario.

The graph shows some oversupply in the earlier years, then supply and demand are very much in balance up to 2030. However, at that time, a substantial number of additional mines will be needed. As outlined in the study, the market will be able to satisfy the demand by raising supply because the known resources of uranium are clearly sufficient.

The study [27] also looked in detail at the situation regarding demand and supply of conversion, enrichment and fuel production facilities. It concluded that for the near term, the existing and planned conversion and enrichment capacities are sufficient, but significant additions will be needed close to 2030. Regarding fuel production, the market is saturated, i.e. there is more than sufficient supply.

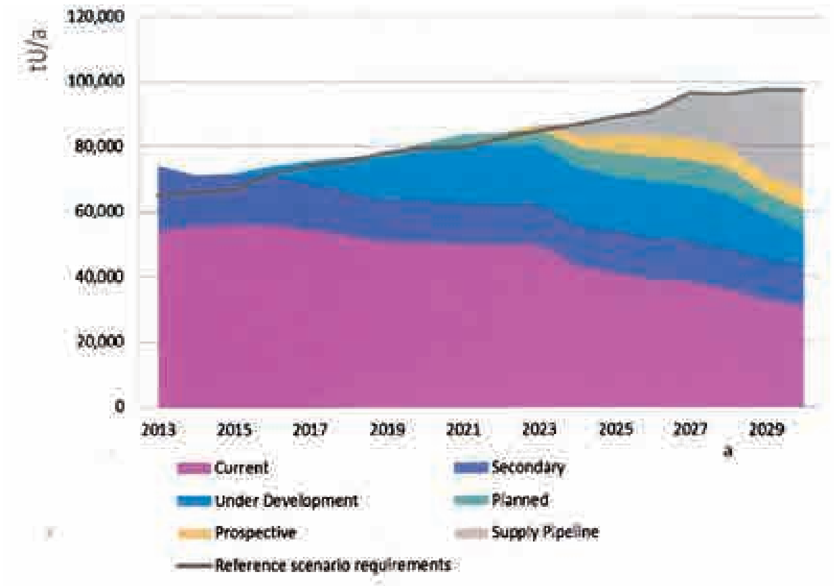

FIG. 12. Comparison of predicted supply by primary resources and secondary sources with demand for the reference scenario [27].

I.5. GENERAL CONCLUSIONS

The uranium resource base and production capacity described in the publications summarized above (additional examples with global scenarios of uranium supply and demand can be found in Refs [33, 35–39]; for regional scenarios, see e.g. Refs. [40, 41]), i.e. the Red Book 2011 [13], the IAEA report Analysis of Uranium Supply to 2050 [11], the OECD/NEA study Trends Towards Sustainability in the Nuclear Fuel Cycle [26] and the WNA study The Global Nuclear Fuel Market [27], is more than adequate to meet projected uranium requirements for the foreseeable future, i.e. up to 2050, even in the case of substantial growth of nuclear power. Taking all conventional and unconventional resources of uranium into account, the resource base amounts to ~4×10^7 tU. Consideration of the potential resources of uranium in sea water of more than 4×10^9 tU makes uranium supply practically unlimited.

However, favourable market conditions are required for known uranium resources to be developed into production facilities in time to meet the projected uranium demand up to 2050, and even more so until the end of the century. This is a plausible scenario, because the history of the last few decades has shown that when uranium prices increase because of predicted shortages, the market will react appropriately, and the necessary uranium production capacity will be realized in time, via increased exploration.

It is important to note that the cost of uranium does not influence significantly the economic competitiveness of nuclear power because its contribution is ~5% of the total production cost of electricity; the main contributors are capital cost (~60%) and maintenance and operation costs (~20%), and the total fuel costs (mining, conversion, enrichment and fuel production) are 15% of the electricity production cost. Thus, large increases in the cost of uranium mined can be tolerated within the nuclear power market.

Appendix II

NON-RENEWABLE MATERIALS: GLOBAL SUPPLY AND DEMAND

This appendix presents a summary of the information documented in the OECD/NEA report [15] published in 2011 on the raw materials needed for a rapid growth in nuclear generating capacity.

II.1. INTRODUCTION

The study [15] collected and analysed information on current raw material requirements and rates of production of these materials for the complete nuclear fuel cycle, and compared them with the requirements arising from a hypothetical tenfold expansion of nuclear generating capacity (from 372 to 3720 GW(e)) that could take place in the latter half of the twenty-first century. For this hypothetical global NES, no limitation of flow of raw materials was defined, thus, global resources are assumed to be continuously available for use in any region.

II.2. SELECTION OF A GLOBAL NUCLEAR ENERGY SYSTEM

Life cycle raw material requirements are documented for currently operating generation II reactors and their associated fuel cycles in environmental product declarations (EPDs) [20]. Owing to the dominance of light water cooled reactors in the existing global fleet and their expected dominance in the future, the study [15] used as a basis a data set from the Swedish Ringhals power plant that consists of 75% PWRs and 25% BWRs that are of generation II design. Thus, the future global NES was assumed to consist of these two types of nuclear reactors only, with an open (or once through) fuel cycle.

II.3. SIMULATION OF GROWTH OF GLOBAL NUCLEAR GENERATING CAPACITY

Several institutions have produced simulations of growth of nuclear generating capacity during the twenty-first century, e.g. the IIASA, WEC, International Energy Agency, OECD/NEA, Intergovernmental Panel on Climate Change (IPCC), Climate Change Science Program and IAEA. The most realistic electricity generation projection found in the study was that of the IIASA/WEC, which forecasts a target capacity of 3720 GW(e) (a tenfold increase compared to 2005) to be reached in 2085 [15].

II.4. GLOBAL DEMAND AND SUPPLY OF RAW MATERIALS

The data set (EPDs) from the Ringhals plant includes information on 68 materials needed for construction, operation and decommissioning of the plant. The demand for each material was increased to fit to a global NES in 2005 (with 372 GW(e) of generating capacity), multiplied by ten to simulate the demand of a global NES by 2085 (with 3720 GW(e) capacity), and compared to the global annual production in 2005. For the following materials, the hypothetical global NES in 2085 would consume more than 1% of the annual global production in 2005: bentonite (86.2%), boron carbide (1.3%), copper (1.7%), fluorite (24.8%), fluorspar 11.0%), gadolinium oxide (4.5%), indium (22.7%), lead (3.2%), manganese (8.3%), nickel (1.5%), silver (3.0%), sodium sulphate (1.2%), titanium oxide (2.4%) and zirconium (6.6%).

The study [15] assumed that any material with a predicted consumption by the global NES in 2085 of more than 4% of the global production in 2005 is a potential candidate for short supply. Based on this criterion, the following six materials of concern were identified: bentonite, fluorite and fluorspar, gadolinium, indium, manganese and zirconium. However, for all these materials, global known resources are large, and it is expected that production would increase in time to meet rising requirements for use in a rapidly increasing global NES.

Additionally, there are opportunities for substitution of scarce materials, e.g. the indium used in control rods can be replaced by hafnium.

The study also discussed the possible changes in demand for raw materials by the introduction of generation III and III+ reactors during the twenty-first century. However, it found that most data on these types of reactors are considered to be commercially confidential and are therefore not available in the public domain. The study concluded that these advanced reactors — although some of them showed higher requirements for steel and concrete — will not limit the (tenfold) development of a global NES, as raw material inputs to steel and concrete were not identified as materials of concern.

For generation IV reactors, the study concluded that raw material requirements are currently not well known, given the early stages of development of such reactors. However, it can be expected that more compact components will result in lower requirements compared to generation II reactors.

II.5. GLOBAL DEMAND AND SUPPLY OF URANIUM

In addition to the raw materials discussed above, the study also evaluated the situation of demand and supply of uranium for a hypothetical global NES consisting of generation II thermal reactors (75% PWRs and 25% BWRs) experiencing a tenfold increase to 3720 GW(e) capacity by 2085. The study estimated that by 2085, an annual production of uranium of over 680×10^3 tU would be required for this hypothetical NES compared to $\sim 40 \times 10^3$ tU/a in 2007. The accumulated demand for uranium would be $\sim 20 \times 10^6$ tU by 2085.

Significant reductions of this demand could be achieved in a thermal reactor fleet by reducing the ^{235}U content of enrichment tails (~20%), increasing the core average burnup (~5%) and the thermal efficiency of the plant (~5%), and by introducing recycling of fissile material by reprocessing of SNF (~30%). The introduction of FRs with breeding rates greater than 1 would further dramatically reduce the demand for mined uranium, leading finally to a negligible amount; for example, using the identified uranium resources[8] ($\sim 6 \times 10^6$ tU in 2008) in a fleet consisting of FRs with a capacity of ~372 GW(e) would enable an operational lifetime of this system of more than 6000 years [26].

A survey of known, conventional uranium resources[9] produced a value of $\sim 16 \times 10^6$ tU in 2007 [15]. Additionally in 2007, unconventional resources of uranium, e.g. in phosphates, were estimated to be $\sim 22 \times 10^6$ tU, which could be mined with prices below US $150/kgU. In sea water, the total amount of uranium is estimated to be more than 4×10^9 tU, but at rather low concentrations of ~3 ppb, leading to prices of US $700/kgU.

Comparing the demand of the hypothetical NES consisting of thermal generation II reactors with an open fuel cycle with the known, conventional resources of uranium, the study concluded that there could be a shortage of needed uranium towards the end of the century. However, the study also acknowledged that an expected shortage of uranium supply would trigger higher prices of uranium, followed by increased exploration, leading to an increase of uranium resources, as has happened several times already since nuclear power was first used.

It is important to note that this study did not take into account that uranium prices are typically only ~5% of the total electricity production costs of a nuclear power plant. This means that higher uranium prices have no significant impact on the competiveness of nuclear power. Therefore, it can be expected that even for this hypothetical NES, sufficient uranium would be available throughout the twenty-first century, especially if the options of how to increase the efficiency of uranium use in the reactor fleet discussed above are realized.

[8] 'Identified uranium resources' refers to deposits delineated by sufficient direct measurements to conduct feasibility studies.

[9] 'Conventional uranium resources' have an established history of production where uranium is a primary product, co-product or an important by-product.

Appendix III

INPRO COLLABORATIVE PROJECT: GAINS

During 2008–2011, INPRO conducted the collaborative project GAINS [3], with participation by Belgium, Canada, China, Czech Republic, France, India, Italy, Japan, Republic of Korea, Russian Federation, Slovakia, Ukraine, USA and the European Commission, with Argentina as an observer.

This appendix summarizes the findings of GAINS, focusing on the issue of demand for uranium resources by possible NESs until the end of the twenty-first century.

III.1. INTRODUCTION

The overall objective of the GAINS project was to develop a standard framework — including a methodological platform, assumptions and boundary conditions — for assessing future NESs, taking into account sustainable development, and to validate the results through sample analyses.

It is to be noted that this project did not have a specific goal to evaluate the potential global supply of uranium until the end of the century and beyond, but focused on the introduction of advanced nuclear reactor technologies and associated fuel cycle strategies in a heterogeneous real world model, with the cooperation of different countries in the nuclear fuel cycle to achieve a number of sustainability goals, including a reduction of the global demand for uranium.

The project used two main models to investigate the possible development of nuclear power during the twenty-first century. One model employed the assumption of a complete homogeneous world, i.e. a world that involves uniform nuclear technology application in each and every country. A second, more realistic, approach was to define a heterogeneous world with three different groups (NG1–NG3) of non-personified countries with different policies regarding the back end of the nuclear fuel cycle. The three groups NG1–NG3 are defined as:

- *NG1: General strategy is to recycle used fuel.* This group plans to build, operate and manage FRs and use fuel recycling facilities and geological disposal facilities for highly radioactive waste (from reprocessing).
- *NG2: General strategy is to either directly dispose of used fuel, or reprocess used fuel abroad.* This group plans to build, operate and manage thermal reactors and geological disposal facilities for highly radioactive waste (in the form of used fuel and/or reprocessing waste) and/or work synergistically with another group to have its fuel recycled.
- *NG3: General strategy is to use fresh fuel, and send used fuel abroad for either recycling or disposal, or the back end strategy is undecided.* This group has no plans to build, operate and manage used fuel recycling facilities or permanent geological disposal facilities for highly radioactive waste. It may obtain fabricated fuel from abroad, and may arrange for export of used fuel.

In addition, in the three group approach, non-synergistic and synergistic behaviours of the world are assumed. The selected models of the world are shown in Fig. 13.

A synergistic world requires communication and material flow between groups of countries, whereas a non-synergistic world would not exchange nuclear materials other than fresh fuel. Figures 14 and 15 illustrate non-synergistic and synergistic models of the world, respectively.

GAINS performed parametric evaluations of a payback time for investments in technology development for FRs and a closed nuclear fuel cycle versus planned national deployment of such technologies. It was concluded that, at least within the twenty-first century, the world is likely to follow the heterogeneous model shown in Fig. 15.

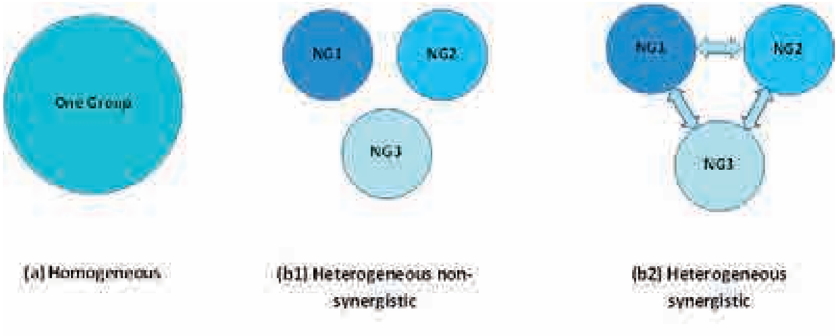

FIG. 13. Selected world models for fuel cycle analysis in GAINS [3].

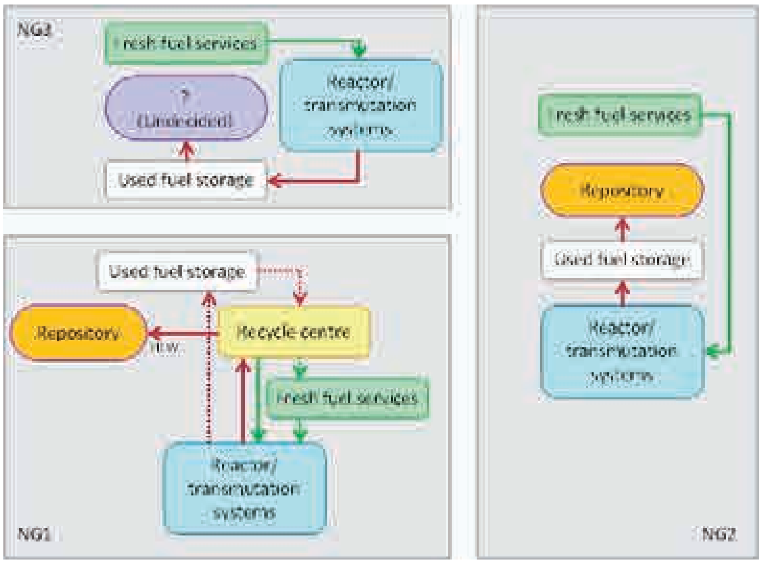

FIG. 14. Heterogeneous model with non-synergistic groups NG1–NG3 [3].

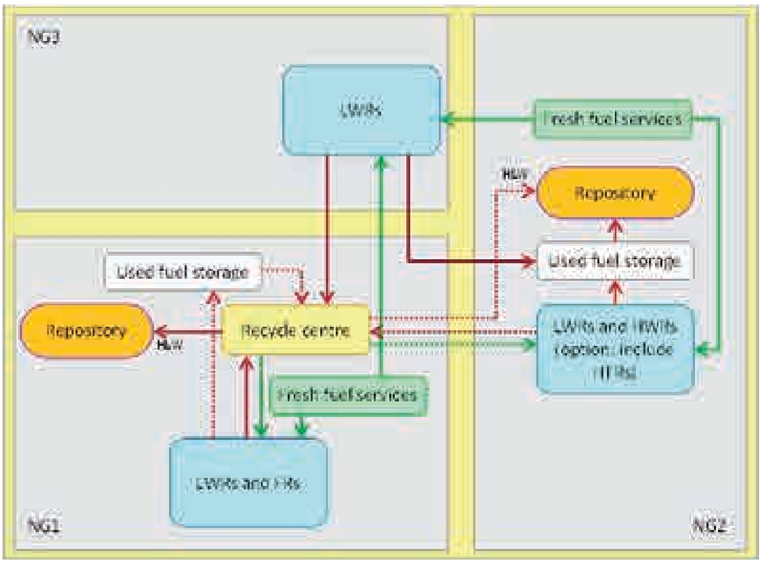

FIG. 15. Heterogeneous model with synergistic groups and specific reactor types and fuel services identified [3]. HTR — high temperature reactor; HWR — heavy water reactor; LWR — light water reactor; MNA — multilateral nuclear approach.

Several analytical tools were used in the GAINS study, but most analytical results were produced using the computer codes MESSAGE, NFCSS and DESAE, available from the IAEA (brief descriptions of these tools can be found in the overview volume of the updated INPRO manual[10]). In many cases, participants in the study also used their national computer codes (Commelini–Sicard (COSI) by France, Dynamic Analysis of Nuclear Energy System Strategies (DANESS) and Verifiable Fuel Cycle Simulation Model (VISION) by the USA, and Tool for Energy Planning Studies (TEPS) by India) to support the project. The GAINS report [3] includes a brief description and the results of cross-verification of all these codes.

III.2. GLOBAL DEMAND FOR POWER SUPPLY BY NUCLEAR ENERGY

The GAINS project, inter alia, evaluated a series of available studies with nuclear power scenarios and documented a brief summary thereof in the final report [3]. The studies included: International Nuclear Fuel Cycle Evaluation [42], Joint Study: Assessment of Nuclear Energy Systems Based on a Closed Nuclear Fuel Cycle with Fast Reactors [43], and Nuclear Energy Development in the Twenty-first Century [44] by the IAEA; Nuclear Fuel Cycle Transition Scenario Studies [45], Strategic and Policy Issues Raised by Transition from Thermal to Fast Reactors [46], Advanced Nuclear Fuel Cycles and Radioactive Waste Management [47], and Trends in the Nuclear Fuel Cycle [48], by the OECD/NEA; Red Impact Synthesis Report by SCK·CEN [49]; and Partitioning and Transmutation European Roadmap for Sustainable Nuclear Energy by the European Commission [50].

Based on comprehensive analysis and intensive discussions of the available projections on nuclear demand in the twenty-first century, GAINS selected two nuclear energy demand scenarios (as illustrated in Fig. 16):

— A *high* nuclear energy demand scenario, a variant of the medium expectation of the IPCC Special Report on Emission Scenarios. In this scenario, global annual nuclear energy generation reaches approximately 700 GW(e) by 2030, 1500 GW(e) by the middle of the century and 5000 GW(e) by 2100.
— A *moderate* nuclear energy demand scenario, assuming approximately 600 GW(e) by 2030, 1000 GW(e) by mid-century and 2500 GW(e) by the end of the century.

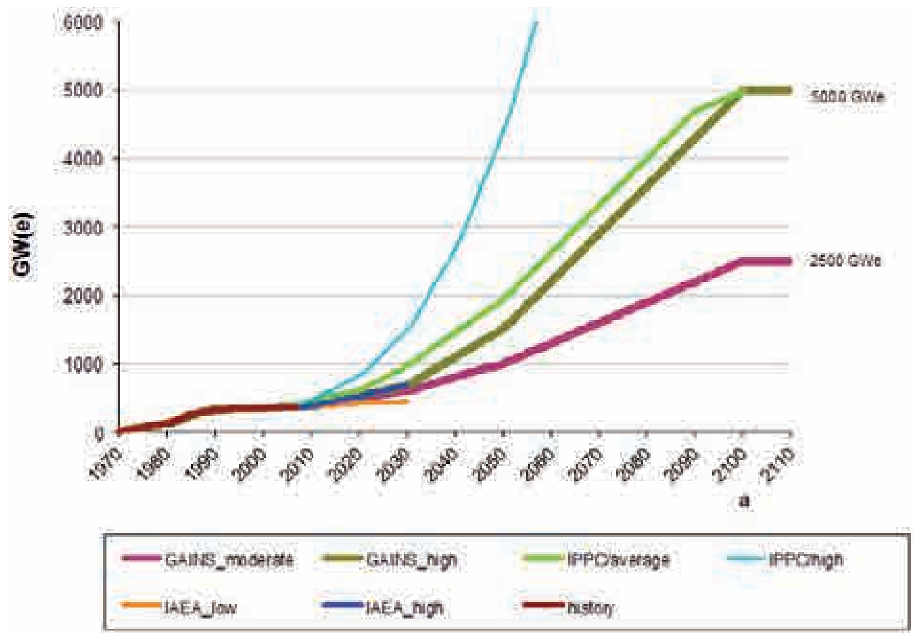

FIG. 16. GAINS scenarios for modelling nuclear power generation in the twenty-first century [3]. IPCC — Intergovernmental Panel on Climate Change.

[10] A publication on this subject is in preparation.

III.3. TYPES OF REACTORS CONSIDERED IN GAINS

GAINS has developed an internationally verified database for material flow analysis of NESs with reactors and nuclear fuel cycles of different types. The reactor types used in basic calculations of GAINS correspond to proven thermal and FR technologies, leaving little doubt as to the feasibility of the corresponding nuclear power plants. The following types of reactors are included in the GAINS database:

— Light water cooled and moderated reactors (LWRs) with low, medium and high burnups (45×10^3–60×10^3 MW·d/t) and different thermal efficiencies;
— Heavy water cooled and moderated reactors (heavy water reactors (HWRs)) with different types of fuel (UO_2, ThO_2, ^{233}U and PuO_2);
— FRs with different conversion factors (1.00–1.16) and different burnups (31–100 MW·d/t).

In all cases, it was assumed that FRs were started from the U–Pu fuel load obtained from reprocessing of the SNF of LWRs.

III.4. SCENARIOS CONSIDERED IN GAINS

As mentioned previously, GAINS looked at homogeneous and heterogeneous scenarios, and for the latter, at non-synergistic and synergistic behaviours.

For a *homogeneous world*, the following NES scenarios were considered: BAU+ (business as usual with present day and advanced LWRs, with '+' standing for the latter) and BAU+–FR (business as usual with introduction of FRs). First, the results for the selected homogeneous scenarios will be presented, followed by the heterogeneous non-synergistic and synergistic scenarios.

III.4.1. BAU+ scenario in a homogeneous world

The homogeneous scenario without introduction of FRs is presented here. The global NES in the BAU+ scenario includes standard LWRs (as installed at 2008) and a conventional HWR, and after 2015, gradually adds advanced types of LWRs called advanced light water reactors (ALWRs), with higher burnups and thermal efficiencies, which completely replace the standard LWRs after 2055. The global power generation is shown in Fig. 17 and the uranium consumption is shown in Fig. 18.

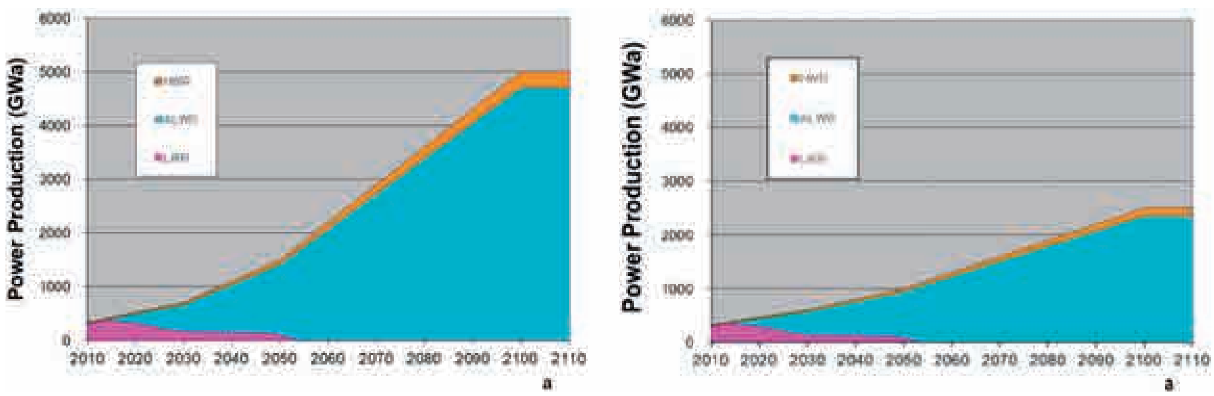

FIG. 17. Power generation in the BAU+ scenario in a homogeneous world (high case on the left, moderate case on the right) [3]. ALWR — advanced light water reactor; HWR — heavy water reactor; LWR — light water reactor.

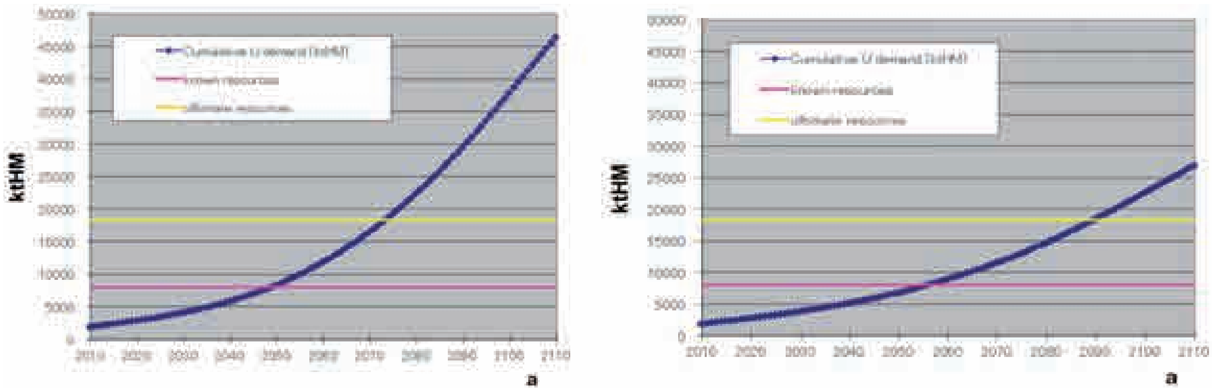

FIG. 18. Total global uranium usage for the BAU+ scenario in a homogeneous world (high case on the left, moderate case on the right) [3]. ktHM — kilotonnes of heavy metal.

The total global uranium consumption reaches 36.1 × 10^6 t and 20.9 × 10^6 t by 2100 for the high and moderate BAU+ cases, respectively.

III.4.2. BAU+–FR scenario in a homogeneous world

The BAU+–FR scenario includes, in addition to FRs, standard LWRs (as installed at 2008) and conventional HWRs, and after 2015, ALWRs with higher burnup, which completely replace the standard LWRs by 2055.

In this scenario, FRs (with a conversion rate of 1.0, a so called break even core design) — in addition to standard LWRs and HWRs — are assumed to be initially introduced in 2021 at a low rate of 1 GW·a of power generation per year for the first 10 years; after 2031, the installation rate is increased to 9.5 GW·a and 19.5 GW·a for the moderate and high cases, respectively; after 2051, the installation rate is only limited by the amount of plutonium available for the FRs and the overall growth rate.

Figure 19 shows the total power generation for the different types of reactors, and Fig. 20 shows the global cumulative uranium consumption together with the limits from the Red Book 2009 (known and ultimate resources) [35].

In this homogeneous scenario BAU+–FR, the total uranium consumption reaches, by 2100, values of ~25 × 10^6 tU and ~15 × 10^6 tU for the high and moderate cases, respectively.

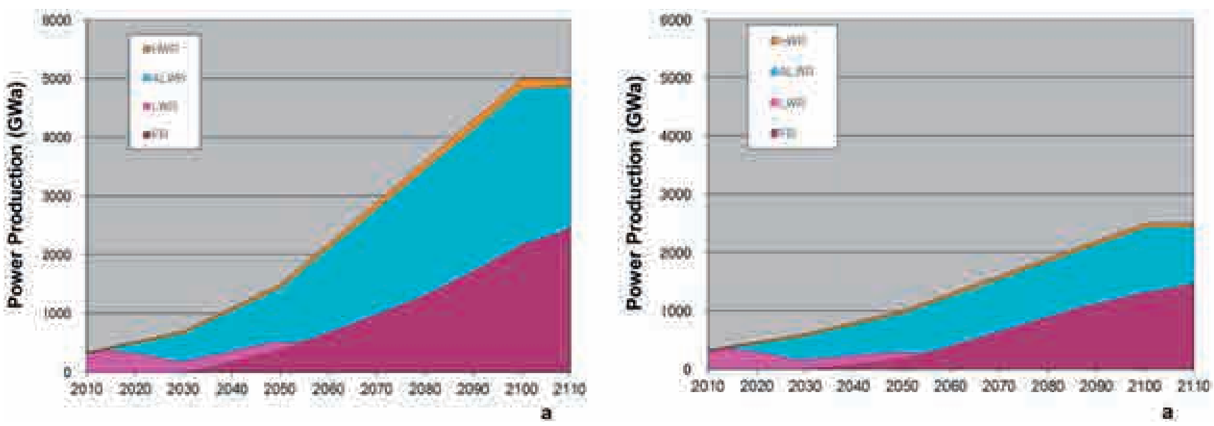

FIG. 19. Power generation for different reactor types in the BAU+–FR scenario in a homogeneous world (high case on the left, moderate case on the right) [3]. ALWR — advanced light water reactor; FR — fast reactor; HWR — heavy water reactor; LWR — light water reactor.

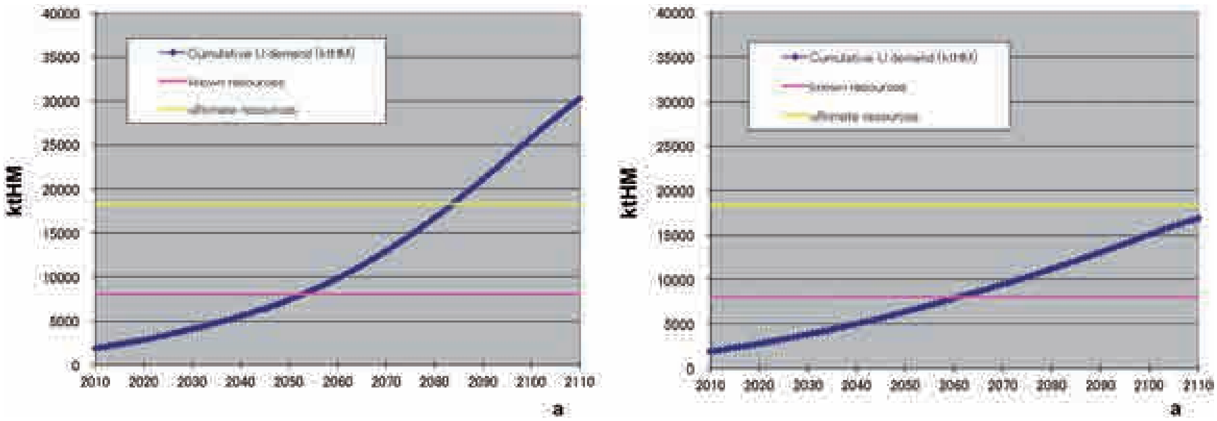

FIG. 20. Total global uranium usage for the BAU+–FR scenario in a homogeneous world (high case on the left, moderate case on the right) [3]. ktHM — kilotonnes of heavy metal.

III.4.3. BAU+–FR scenario in a heterogeneous world

The heterogeneous world model extends the BAU+–FR homogeneous scenario by dividing the world into three non-geographic groups, NG1–NG3, where the countries within a group all adopt the same fuel cycle strategy (see Section III.1 above). The first nuclear power group (NG1) adopts recycling and a transition to FRs, as assumed in the (global) homogeneous BAU+–FR scenario. NG2 continues with the BAU+ strategy of a once through fuel cycle based on standard LWRs and HWRs, plus ALWRs, without recycling. NG3 starts to introduce LWRs and HWRs beginning in 2008 and replacing them by ALWRs after 2015. The 6% share of global HWRs are all modelled as part of NG2.

The heterogeneous cases use the same overall nuclear power demand curves for high growth and moderate growth as the homogeneous cases. The contributions of each group NG1–NG3 to the global nuclear power generation during the twenty-first century are based on extrapolation of data available in 2009 and on expert evaluations carried out within GAINS: by 2100 — NG1:NG2:NG3 = 0.4:0.4:0.2.

As stated previously, in the heterogeneous model, a non-synergistic and a synergistic world were considered in GAINS. The results of the non-synergistic scenarios in a heterogeneous world will be discussed first.

III.4.3.1. Heterogeneous BAU+–FR scenario in a non-synergistic world

For the non-synergistic world model, no movement of used nuclear fuel occurs between groups NG1 and NG2 in this scenario. This limits the amount of LWR and ALWR spent fuel available in NG1 for reprocessing and starting of FRs. An example of such a heterogeneous non-synergistic global NES was presented in Fig. 14 above.

The total power generation during the century globally and for three non-geographical groups are shown in Fig. 21.

Figure 21 illustrates the assumptions made for this scenario. The groups NG3 and NG2 install standard LWRs, ALWRs and HWRs, and only group NG1 also installs FRs with a conversion rate of 1.0 (a break even FR design). The combined power generation of the three groups is the same as that defined for the homogeneous case.

Figure 22 shows the cumulative uranium consumption of this non-synergistic heterogeneous scenario BAU+–FR.

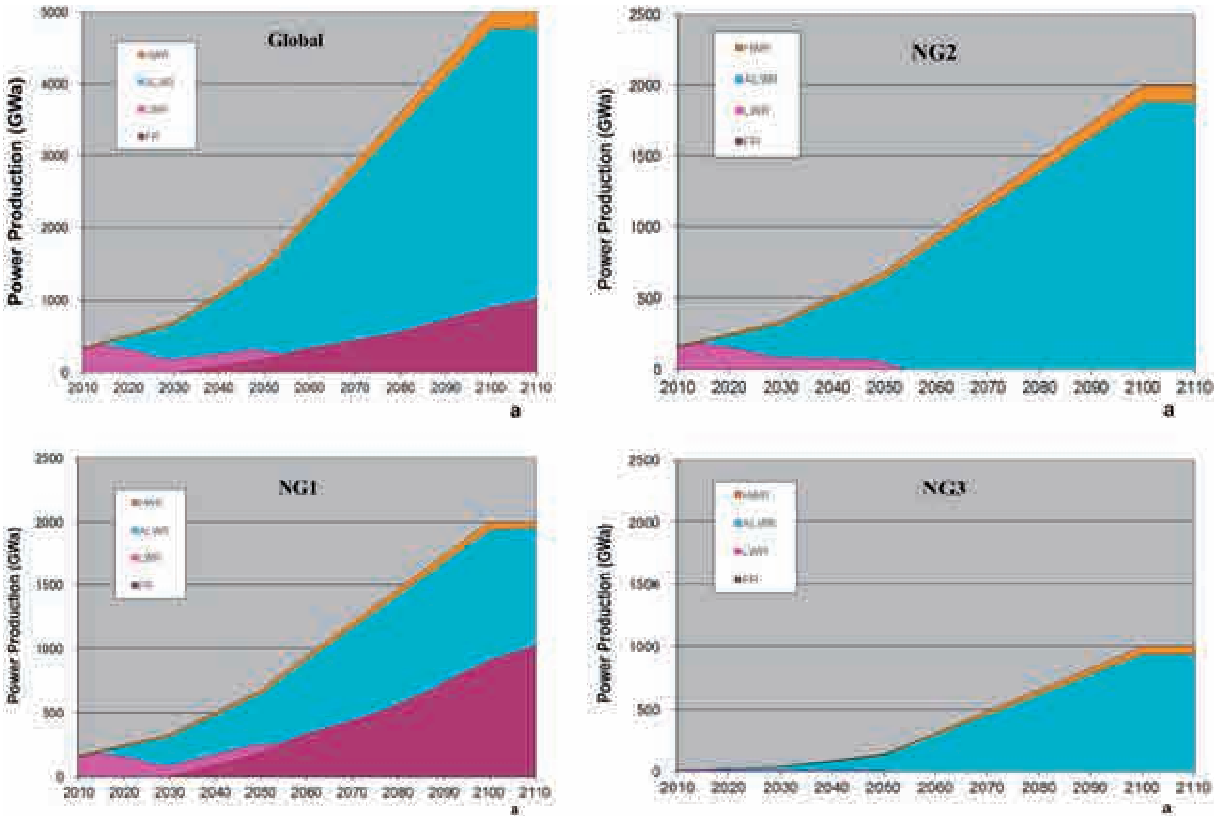

FIG. 21. Power generation for different types of reactors and groups in the BAU+–FR scenario in a non-synergistic heterogeneous world [3]. ALWR — advanced light water reactor; FR — fast reactor; HWR — heavy water reactor; LWR — light water reactor.

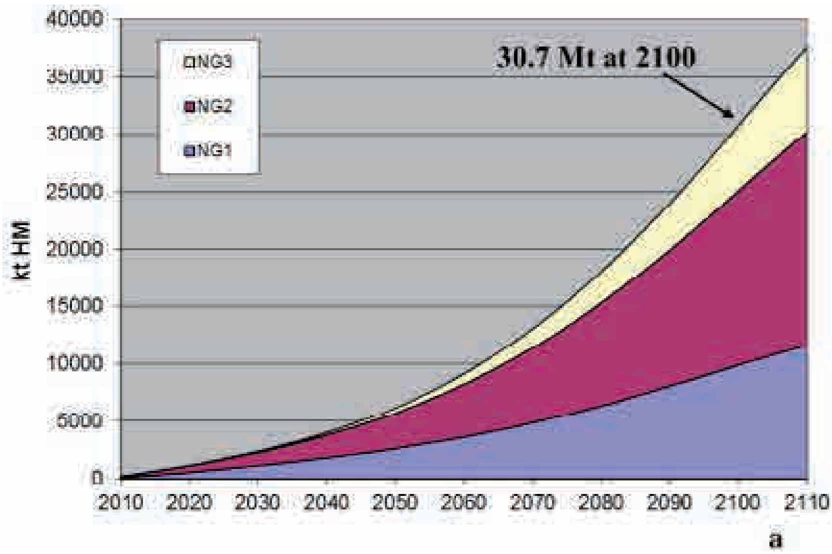

FIG. 22. Cumulative uranium consumption for the non-synergistic heterogeneous scenario BAU+–FR for the high case [3]. ktHM — kilotonnes of heavy metal.

The value of global uranium consumption by 2100 for the heterogeneous non-synergistic scenario BAU+–FR (Fig. 22) is ~31 × 10^6 tU for the high case (and ~17 × 10^6 tU for the moderate case, not shown in Fig. 22). These values are between the values for the homogeneous BAU+ scenario (Fig. 18, ~36.1 × 10^6 tU for the high case and

~21 × 10^6 tU for the moderate case) and the values for the homogeneous BAU+–FR scenario (Fig. 20, ~24 × 10^6 tU for the high case and ~14 × 10^6 tU for the moderate case). This means that the full potential of FRs to reduce the need for uranium resources cannot be achieved in this scenario BAU+–FR. As stated above, this is caused by the non-availability of sufficient spent fuel to be reprocessed (to produce MOX fuel) in the group NG1 in this non-synergistic heterogeneous model.

III.4.3.2. Heterogeneous BAU+–FR scenario in a synergistic world

The heterogeneous synergistic case builds upon the non-synergistic case of Section III.4.3.1. The key difference is that movement of used nuclear fuel is allowed between the different groups NG1–NG3 (synergism). This free movement of material results in improvement of the ability of each group to follow its selected fuel cycle strategies. An example of the NES for this scenario was presented in Fig. 15 above.

Figure 23 shows the power generation globally and in the three groups NG1–NG3, and illustrates that FRs are assumed to be introduced only into the group NG1 after 2030, and that standard LWRs are replaced by ALWRs starting at around 2015 in all groups.

Figure 24 shows the cumulative uranium consumption for the heterogeneous synergistic BAU+–FR scenario. In comparison to the non-synergistic scenario (Fig. 22), this synergistic scenario results in a reduction of uranium demand by 4.3 × 10^6 tU.

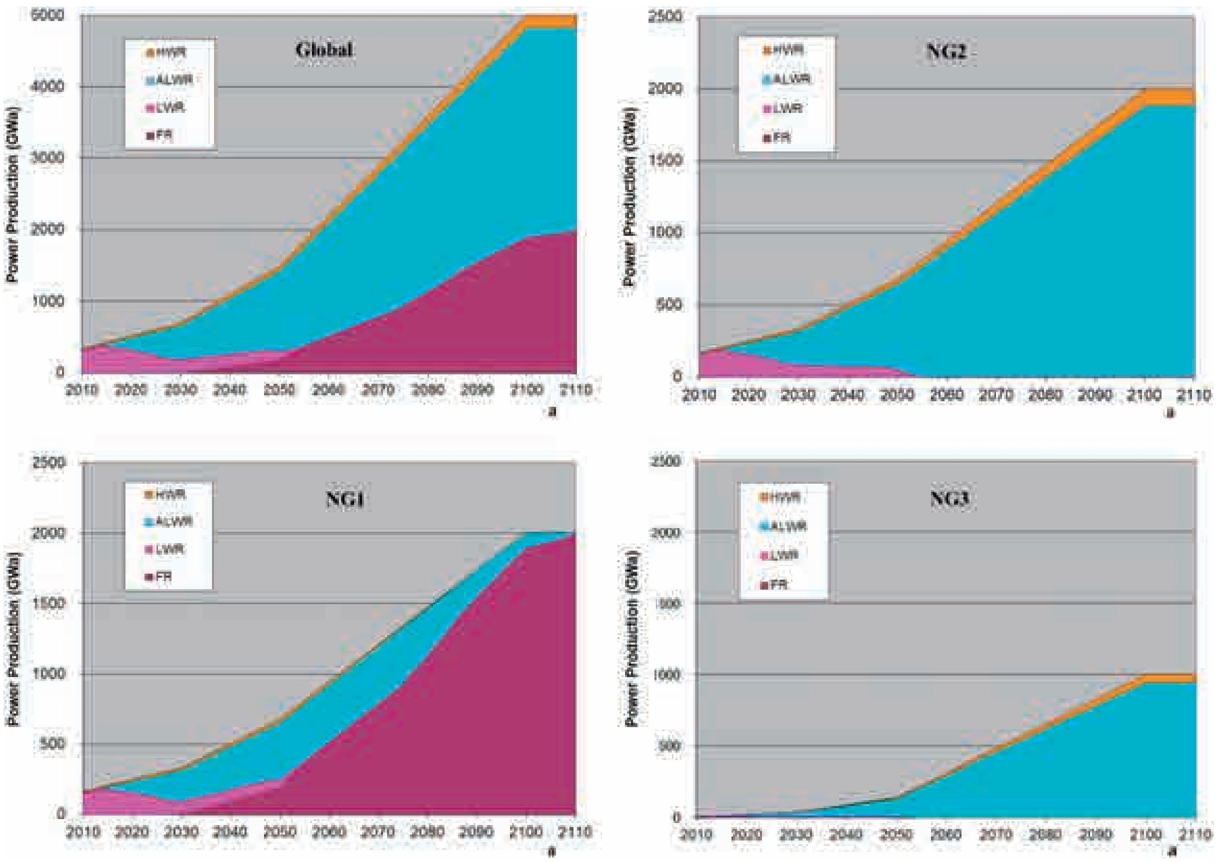

FIG. 23. Power generation for groups NG1–NG3 and total generation in the synergistic heterogeneous scenario BAU+–FR in the high case [3]. ALWR — advanced light water reactor; FR — fast reactor; HWR — heavy water reactor; LWR — light water reactor.

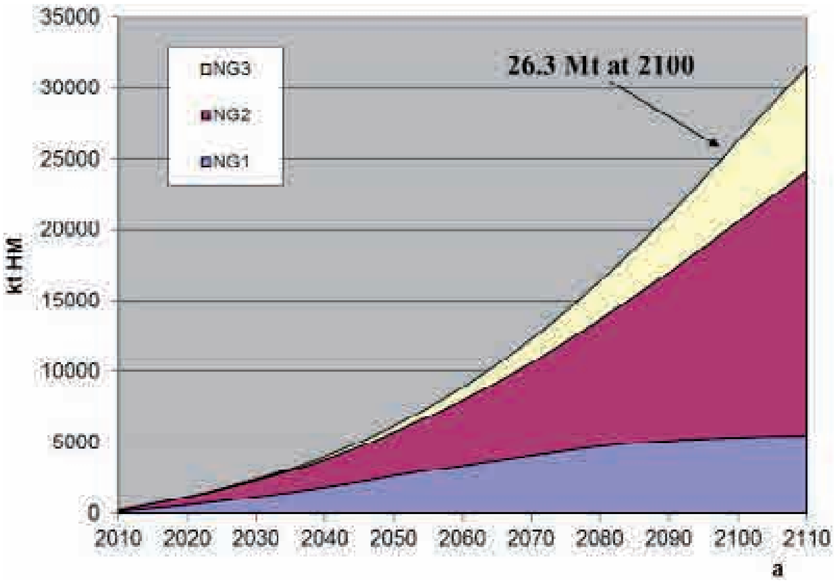

FIG. 24. Cumulative uranium consumption for the synergistic heterogeneous scenario BAU+–FR in the high case [3]. ktHM — kilotonnes of heavy metal.

III.4.4. Summary of selected scenarios considered in GAINS

A summary of results regarding the global uranium consumption for selected scenarios is presented in Table 7. In scenario 1, called BAU+, only thermal reactors (standard LWRs and HWRs) are assumed to be built during the twenty-first century plus ALWRs with increased burnups and higher efficiencies. Scenarios 2–4 include the introduction of FRs with different conversion rates and burnups into a global NES.

TABLE 7. SUMMARY OF SELECTED SENSITIVITY STUDIES IN GAINS ON GLOBAL DEMAND OF URANIUM BY 2100

Scenario			Homogeneous model	Heterogeneous model Non-synergistic	Heterogeneous model Synergistic
			Natural uranium demand by 2100 ($\times 10^6$ tU)		
1	BAU+	High Moderate	36.1 20.9	36.1 20.9	36.1 20.9
2	BAU+–FR (CNR=1)	High Moderate	24.1 13.4	30.8 17.2	26.3 14.9
3	BAU+–FR (CNR=1.2)	High Moderate	21.2 11.3	29.4 16.2	26.3 14.9
4	BAU+–FR (CNR=1.2, high burnup)	High Moderate	22.1 11.8	29.9 16.5	26.3 14.9

Note: Case 1 corresponds to the scenario BAU+ presented in Section III.4.1; case 2 corresponds to the scenario BAU+–FR presented in Section III.4.3; case 3 is similar to case 2, but for a conversion rate (CNR) of 1.2 in the fast reactors installed; case 4 is similar to case 2, but for a CNR of 1.2 and a high burnup in the fast reactors installed.

In all cases, the homogeneous model shows the lowest global consumption of uranium by 2100 in comparison with the heterogeneous models; therefore, the homogeneous model is obviously too optimistic. The non-synergistic heterogeneous model demonstrates that the full potential of FRs to save uranium resources cannot be achieved because no exchange of nuclear material between countries takes place in this model. The synergistic heterogeneous model illustrates the significant potential of FRs to save uranium resources in a world that is freely exchanging nuclear material, i.e. fresh and used fuel. As has already been mentioned, one of the main conclusions of the GAINS project was that within the twenty-first century, the world is likely to follow the heterogeneous model, with the degree of cooperation between countries (i.e. the degree of synergism) still being an open question [3].

Although GAINS has not introduced any limits on natural uranium resources (assuming that their extended use would result in an overall uranium cost increase rather than physical depletion), the results of Table 7 could still be analysed, just as an example, against the data on the natural uranium resources from the Red Book.

Based on the Red Book 2009, the identified resources of uranium could be defined as ~7 × 10^6 tU, and the sum of all conventional resources as ~18 × 10^6 tU [35]. Then, if it is assumed that natural uranium from conventional resources would have reasonably low costs and natural uranium from non-conventional resources would have much higher costs, it may make sense to select 18 × 10^6 tU as a sort of a boundary against which the Table 7 data could be analysed.

In all moderate cases discussed in GAINS, a global NES with predicted nuclear generation of 2500 GW(e) by 2100 would most likely not run over the boundary of 18 × 10^6 tU during this century, especially if FRs are introduced in a number of countries. However, this is not true for the high cases with a predicted nuclear generation of 5000 GW(e) by 2100. To keep natural uranium consumption within the 18 × 10^6 tU boundary in cases of such a high growth rate of global nuclear power would definitely require the timely introduction of FRs in a number of countries throughout the world. On a more positive note, recent developments indicate that by around 2030, commercial deployment of FRs is likely to start in a number of technology holder countries around the world.

It should be noted that very similar conclusions were obtained in an earlier IAEA study, Nuclear Energy Development in the 21st Century: Global Scenarios and Regional Trends [4].

III.5. CONCLUSION

The GAINS project has developed a framework for analysing global NES architecture and has shown — through sample analyses — that sustainability is more easily achieved on a global scale with collaboration (synergistic approach) among countries with different policies regarding the back end of the fuel cycle.

In comparison to a non-synergistic approach, the synergistic approach with a worldwide free flow of nuclear material can, inter alia, result in more effective utilization of fissile/fertile material resources in the global system by making SNF available for recycling and reuse in nuclear reactors that otherwise might be disposed of as waste.

A synergistic approach could facilitate a partial solution to the problem of accumulating SNF inventories and associated waste disposal in each individual country with a nuclear power programme. Countries with smaller programmes could avoid developing their own nuclear waste management infrastructure by returning SNF to the countries that supplied the fuel and who would recycle the returned fuel for further use in national FR programmes. Given the current political situation, a high level waste facility would still be required; however, this would be for disposal of fission products (only).

Regarding global uranium resources and consumption, it can be concluded that total conventional (ultimate) resources of uranium (~17 × 10^6 tU as recorded in the Red Book 2009 [35]) are almost sufficient to enable the operation of a global NES based on advanced thermal reactors without running out of a fuel supply until the end of the twenty-first century, if the total installed capacity of nuclear power at the end of the century does not exceed 2500 GW(e) (called the moderate case in GAINS), which corresponds to about a sixfold increase by 2100 over the installed nuclear capacity in 2013. If the growth rate of nuclear power increases above such a value, a timely introduction of FRs in specific countries that master this technology is capable of mitigating any shortage of reasonably priced natural uranium.

It should be noted that non-conventional resources of uranium (see Appendix I) discussed in the Red Book 2011 (~22×10^6 tU) [13], e.g. in phosphates and black shale, which would be globally available at higher prices of uranium mining would increase the available uranium resources considerably. If uranium from sea water is taken into account (more than 4 billion tonnes), the global resource of uranium becomes practically unlimited.

It is also a known fact that uranium prices do not significantly influence the cost of electricity production by nuclear power plants, as the uranium price is below 5% of the total electricity generation cost of a nuclear power plant.[11] The capital costs are the dominant factor at up to ~60%, operation and maintenance costs are ~25%, and the remaining costs of the nuclear fuel of 15% include the costs of uranium, conversion, enrichment and fuel element production. Thus, an increase of uranium prices might not be an obstacle for enlarging a global NES, at least with nuclear power plants based on state of the art LWR technologies.

[11] This value corresponds to LWRs with an enrichment level below 5% of ^{235}U. Some advanced reactors, such as high temperature gas cooled reactors and FRs starting from an enriched uranium load will have a fuel enrichment that is several times higher than that of a typical LWR.

Appendix IV

EFFICIENCY OF URANIUM USE

This appendix presents examples of the end uses of uranium (normalized by energy delivered in GW·a) in a simple NES consisting of a nuclear power plant with an open (once through) uranium fuel cycle analysed with the NEST code described in Ref. [5].

IV.1. DESCRIPTION OF THE NUCLEAR ENERGY SYSTEM

Figure 25 illustrates the mass flow of front end facilities of an NES starting with mining and ending with the nuclear power plant.

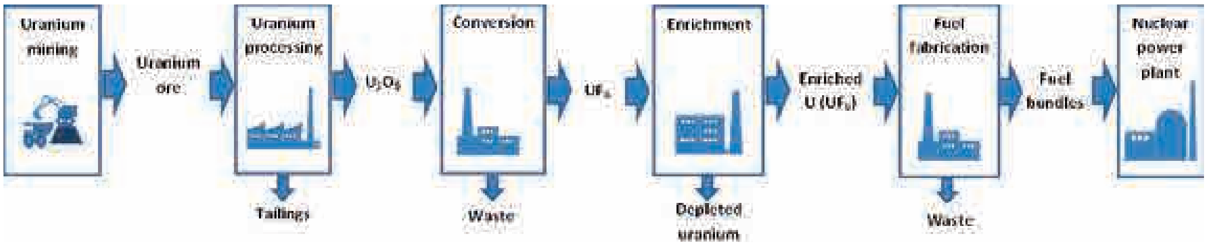

FIG. 25. Fuel production chain for a light water reactor using uranium fuel in an open fuel cycle.

The characteristics of the individual nuclear fuel cycle facilities that are typical for a current NES with an open fuel cycle are presented in Table 8 (input data necessary for calculation).

TABLE 8. CHARACTERISTICS OF INDIVIDUAL FUEL CYCLE FACILITIES IN A TYPICAL CURRENT NUCLEAR ENERGY SYSTEM

Front end fuel cycle stages and nuclear power plant operation	Parameter	Name	Value
Mining and processing	U-235 concentration in natural isotopes blend (%/100)	ε_F	0.00711
	Losses at extraction (%/100)	l_1	0.20[a]
Conversion	Losses (%/100)	l_2	0.005
Enrichment	U-235 concentration in fuel (%/100)	ε_P	0.04
	U-235 concentration in depleted uranium (%/100)	ε_T	0.0025
	Losses (%/100)	l_3	0
Fuel fabrication	Losses (%/100)	l_4	0.01
Nuclear power plant (energy conversion)	Unloaded fuel average burnup (MW·d/kg)	Q	45
	Nuclear power plant net thermal efficiency (%/100)	η	0.32

[a] The lower margin of a range provided in Ref. [13] (20–35% depending on the technology) is used for this example. ‘0.20’ corresponds to open pit mining with conventional milling.

IV.2. MATERIAL BALANCE OF THE NUCLEAR ENERGY SYSTEM

A detailed algorithm of the material balance calculation for different options of the fuel cycle, including the front end of a once through fuel cycle is described in Appendix II of the INPRO methodology manual on economics [5].

The equation describing the link between the mass of heavy metals at different stages of the front end of the fuel cycle (HM_k),

$$HM_k = \prod_{j=k}^{N\ \text{stages}} HMI_j^{j+1} \cdot \left(1 + l_j\right), \tag{1}$$

can be easily converted into a formula for the amount of natural uranium spent on the production of an electricity unit. Here, HMI_j^{j+1} is the quantity of heavy metal necessary at stage j to produce 1 kg of fuel at the next stage (j+1) without accounting for losses (i.e. in an 'ideal' case); l_j is the loss of uranium during processing at every stage of the front end (e.g. j=2 losses at uranium conversion); all values are input data to NEST.

The equation estimating the amount of natural uranium necessary to produce 1 GW·a of electricity in a once through fuel cycle (HM_0) is the following:

$$HM_0 = \frac{365 \times 10^3 \cdot \dfrac{\varepsilon_P - \varepsilon_T}{\varepsilon_F - \varepsilon_T} \cdot \left(1 + l_1\right) \cdot \left(1 + l_2\right) \cdot \left(1 + l_3\right) \cdot \left(1 + l_4\right)}{\eta \cdot Q}, \tag{2}$$

where 365 × 10^3 is a coefficient converting GW·a into MW·d, and the rest of parameters are described in Table 8 (for simplicity, the first core fuel and reload fuel are not differentiated between here).

Numerical calculation based on the input data in Table 8 yields that approximately 2.5 × 10^5 kg of natural uranium is necessary to produce 1 GW·a of electricity. For completeness, it should be mentioned that such a result can be obtained not just by using NEST algorithms, and the INPRO assessors may use other tools, e.g. NFCSS developed by the IAEA and available on the IAEA web site [10].

Thus, the NES retrieves 34.9 GW·h from 1 tU. This value of 34.9 GW·h/tU corresponds to the value of U_0 defined in criterion CR1.4 (Section 3.2.4 of this publication).

IV.3. SENSITIVITY OF THE END USE OF URANIUM IN THE NUCLEAR ENERGY SYSTEM

By looking at Table 8 (characteristics of NES facilities), it is obvious how the efficiency of the NES could be increased: firstly by reducing the losses in the fuel cycle facilities, i.e. in the processing, conversion and fuel fabrication facility, and by reducing the enrichment in the tailings of the enrichment facility, i.e. in the depleted uranium; and secondly, by increasing the nuclear power plant's thermal efficiency and average burnup of the nuclear fuel to be unloaded.

In Table 9, the sensitivities of the characteristics of the NES fuel cycle facilities to increase the efficiency of the uranium end use are presented. In the base case, the NES end use of natural uranium amounts to 251.1 tU to generate 1 GW·a of electricity. Table 9 presents the change of the NES end use of uranium in the cases when the losses of uranium in the fuel cycle facilities are decreased by 10% and 20%.

TABLE 9. CHANGE OF NATURAL URANIUM END USE IN NUCLEAR ENERGY SYSTEMS BY REDUCTION OF LOSSES IN THE NUCLEAR FUEL CYCLE FACILITIES

Fuel cycle stages	Base case losses (%/100)	Reduction by 10%			Reduction by 20%		
		Losses (%/100)	Uranium end use (tU)	Reduction of U end use (tU)	Losses (%/100)	Uranium end use (tU)	Reduction of U end use (tU)
Processing	0.20	0.18	247.0	4.1	0.16	242.8	8.3
Conversion	0.005	0.0045	251.0	0.1	0.004	250.9	0.2
Enrichment	0.0025 (tails assay)	0.00225	239.8	11.3	0.002	229.6	21.5
Fuel fabrication	0.01	0.009	250.9	0.2	0.008	250.6	0.5

Table 10 presents the sensitivities of the characteristics of the nuclear power plant with regard to the end use of natural uranium. The influences of two characteristics are studied, namely, the thermal efficiency of the plant and the (core average) burnup of the nuclear fuel.

TABLE 10. CHANGE OF NATURAL URANIUM END USE IN NUCLEAR ENERGY SYSTEMS BY INCREASING THERMAL EFFICIENCY AND BURNUP IN THE NUCLEAR POWER PLANT

Nuclear power plant parameter	Base case value	Increase by 10%			Increase by 20%		
		Parameter value	Uranium end use (tU)	Reduction of uranium end use (tU)	Parameter value	Uranium end use (tU)	Reduction of uranium end use (tU)
Thermal efficiency	0.32%/100	0.352%/100	228.3	22.8	0.384%/100	209.3	41.8
Average burnup	45 MW·d/kg	49.5 MW·d/kg	228.3	22.8	54 MW·d/kg	209.3	41.8

A comparison of the results in Table 9 with Table 10 indicates that the highest relative increase of efficiency (or reduction) of natural uranium end use in the NES can be achieved by an increase of thermal efficiency of the power plant or by an increase of burnup in the fuel followed by a reduction of the tails assay in the enrichment facility.

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GLOSSARY

assessment. An assessment using the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) methodology is a process of making a judgement about the long term sustainability of a nuclear energy system (NES). In principle, analyses using analytical tools are not part of an INPRO assessment, but could provide necessary input for the assessment. The assessment of an NES is done at the criterion (CR) level of the INPRO methodology. In the case of a numerical CR, the assessment process consists of a comparison of the value of an indicator (IN) with the value of the acceptance limit (AL) of a CR. In the case of a logical CR — mostly phrased in the form of a question — the assessment is done by answering the question raised.

assessor. The INPRO assessor is an expert or a team of experts applying the INPRO methodology in an NES assessment. The assessor is typically a member of the academic society of a country such as an academy of science, or from a nuclear research centre, but the assessor could also be from a utility or an organization of the regulator or supplier.

basic principle (BP). A BP of the INPRO methodology is a statement of a general goal that must be achieved in an NES to be sustainable in the long term and which provides broad guidance for the necessary development (or a design feature thereof). The wording of a BP always utilizes the verb 'shall' or 'must'.[1]

criterion (CR). A CR enables the INPRO assessor to determine whether and how well a user requirement is being met by a given NES. A CR consists of an IN and an AL. An IN may be based on a single parameter, on an aggregate variable or on a status statement. ALs could be international or national regulatory limits or defined by the INPRO methodology. Two types of CR are distinguished: numerical and logical. A numerical CR has an IN and an AL that is based on a measured or calculated value that reflects a property of an NES. A logical CR is associated with some important feature of (or measure for) an NES and is usually presented in the form of a question that has to be answered positively. Some CR have evaluation parameters associated with them to simplify the assessment process.

environment. The term 'environment' is defined, along with national laws and regulations of various jurisdictions, as including all of the following components: human beings; non-human biota (animals and plants); abiotic components, including soil, water, air, natural resources and landscape; and interactions among these components.

holistic. The INPRO methodology is defined as a holistic approach to achieve long term sustainability of an NES. Holistic means that all aspects of a nuclear power programme at least until the end of the twenty-first century must be considered, looking at a complete fuel cycle of an NES during the lifetime of all its facilities, and covering all areas of the INPRO methodology from economics through to safety.

nuclear energy system (NES). An NES comprises the complete spectrum of nuclear facilities and associated legal and institutional measures (infrastructure). Nuclear facilities include, in addition to nuclear reactors, facilities for mining and processing, conversion and enrichment of uranium, manufacturing of nuclear fuel, reprocessing of nuclear fuel (if a closed nuclear fuel cycle is used) and related materials management activities, including transportation and waste management (storage and disposal). Legal measures consist of the national nuclear law, international agreements, treaties and conventions; institutional measures include the corresponding national institutions such as regulatory bodies.

sustainability. Within the INPRO methodology, to confirm the sustainability of an NES, the system must be capable of operating at least until the end of the twenty-first century.

[1] Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

user requirement (UR). A UR defines what should be done to meet the target/goal of the INPRO methodology BP and is directed at specific institutions (users) involved in nuclear power development, deployment and operation, i.e. the developers/designers, government agencies, facility operators and support industries. The wording of a UR utilizes the verb ‘should’.

ABBREVIATIONS

AL	acceptance limit
ALWR	advanced light water reactor
BAU	business as usual
BP	basic principle
BWR	boiling water reactor
CR	criterion
DESAE	Dynamic Energy System – Atomic Energy
EPBT	energy payback time
EPD	environmental product declaration
EPR	energy profit ratio
FR	fast reactor
GAINS	Global Architectures of Innovative Nuclear Energy Systems with Thermal and Fast Reactors, Including a Closed Fuel Cycle
HEU	highly enriched uranium
HWR	heavy water reactor
IIASA	International Institute for Applied Systems Analysis
IN	indicator
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IPCC	Intergovernmental Panel on Climate Change
IR	inferred resource
kgU	kilograms of uranium
LEU	low enriched uranium
LWR	light water reactor
MA	minor actinide
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MOX	mixed oxide
NES	nuclear energy system
NEST	Nuclear Economics Support Tool
NFCSS	Nuclear Fuel Cycle Simulation System
OECD/NEA	OECD Nuclear Energy Agency
ppb	parts per billion
PR	prognosticated resource
PWR	pressurized water reactor
RAR	reasonable assured resource
REPU	reprocessed uranium
RD&D	research, development and demonstration
SNF	spent nuclear fuel
SR	speculative resource
TRU	transuranic
tU	tonnes of natural uranium
UNFC-2009	United Nations Framework Classification for Fossil Energy and Mineral Resources 2009
UR	user requirement
WEC	World Energy Council
WNA	World Nuclear Association

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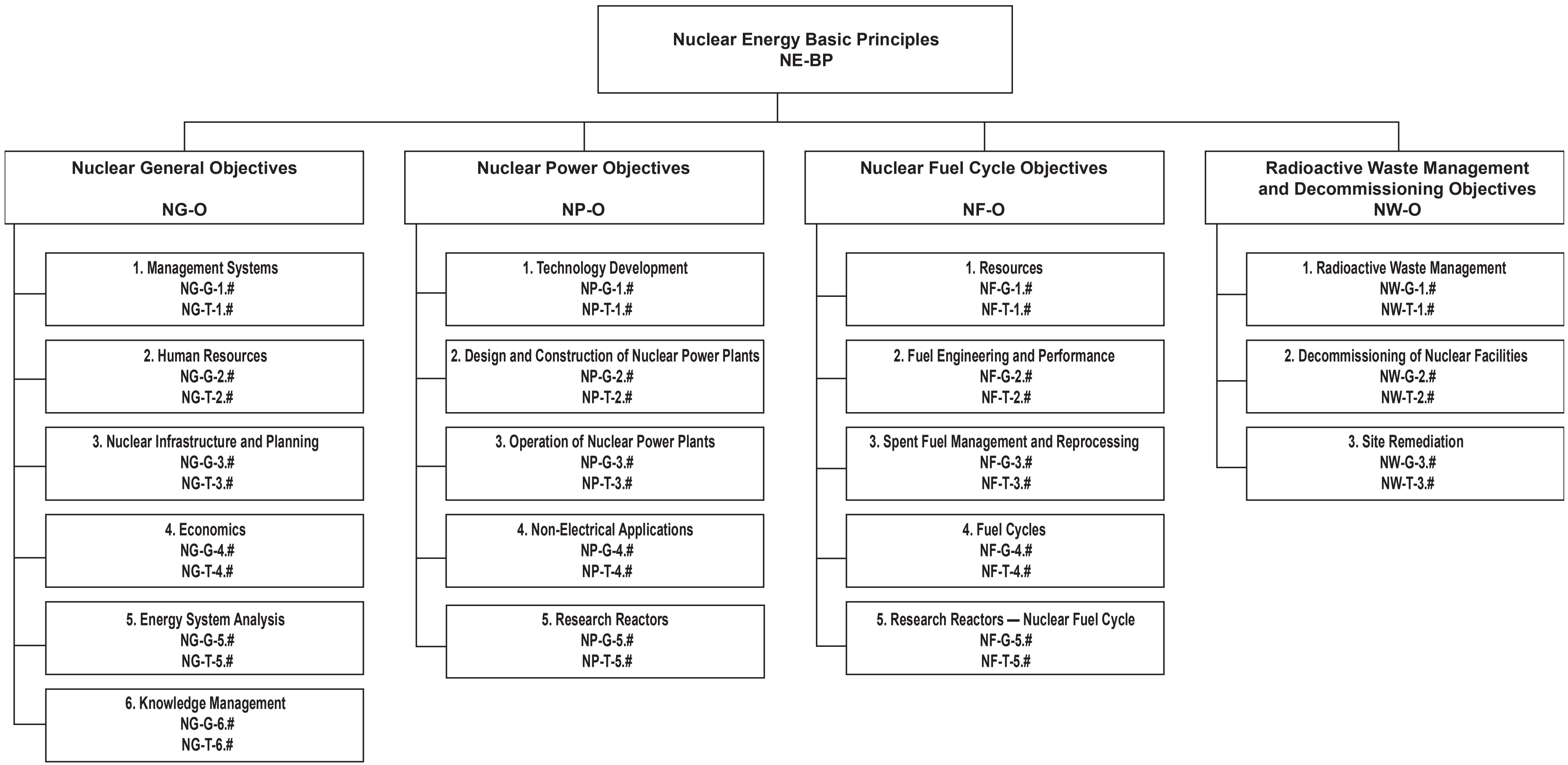

Key

BP: Basic Principles
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Nos 1-6: Topic designations
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