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DEVELOPING ROADMAPS TO ENHANCE NUCLEAR ENERGY SUSTAINABILITY: FINAL REPORT OF THE INPRO COLLABORATIVE PROJECT ROADMAPS

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

IAEA NUCLEAR ENERGY SERIES No. NG-T-3.22

DEVELOPING ROADMAPS TO ENHANCE NUCLEAR ENERGY SUSTAINABILITY: FINAL REPORT OF THE INPRO COLLABORATIVE PROJECT ROADMAPS

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FOREWORD

The IAEA's statutory role is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". Among other functions, the IAEA is authorized to "foster the exchange of scientific and technical information on peaceful uses of atomic energy". One way this is achieved is through a range of technical publications including the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series comprises publications designed to further the use of nuclear technologies in support of sustainable development, to advance nuclear science and technology, catalyse innovation and build capacity to support the existing and expanded use of nuclear power and nuclear science applications. The publications include information covering all policy, technological and management aspects of the definition and implementation of activities involving the peaceful use of nuclear technology.

The IAEA safety standards establish fundamental principles, requirements and recommendations to ensure nuclear safety and serve as a global reference for protecting people and the environment from harmful effects of ionizing radiation.

When IAEA Nuclear Energy Series publications address safety, it is ensured that the IAEA safety standards are referred to as the current boundary conditions for the application of nuclear technology.

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was launched in November 2000 by the IAEA. Since then, INPRO activities have been repeatedly endorsed by the IAEA General Conference and by the General Assembly of the United Nations. The objectives of INPRO are to help ensure that nuclear energy is available to contribute to meeting energy needs in the twenty-first century in a sustainable manner, and to bring together technology holders and users so that they can jointly consider the international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles.

The INPRO collaborative project Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems (ROADMAPS), implemented between 2014 and 2019, developed a structured approach to enhance nuclear energy sustainability, providing models for international cooperation and a template for documenting actions, scope of work and timeframes for specific collaborative efforts by particular stakeholders — the roadmap template.

Using this approach, interested Member States performed national case studies to represent and examine long term national nuclear energy strategy in a specified format to move toward globally sustainable nuclear energy systems. The roadmap template has been applied to global, regional and national cases and for performing cross-cutting analyses of models of cooperation between countries in the front end and the back end of the nuclear fuel cycle.

The ROADMAPS collaborative project integrates the results of years of INPRO's work on global scenarios, facilitating further application of these results by Member States. It is a logical continuation of INPRO's work on the Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS) project, the Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES) project and the Key Indicators for Innovative Nuclear Energy Systems (KIND) project. This publication presents the outputs of the ROADMAPS collaborative project. In addition, it is accompanied by on-line supplementary files that can be found on the publication's individual web page at www.iaea.org/publications. The IAEA officers responsible for this publication were V. Kuznetsov and G. Fesenko of the Division of Nuclear Power.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

This publication documents the scope and outputs of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) collaborative project Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems (ROADMAPS). The ROADMAPS project was implemented between 2014 and 2019 by experts nominated by Armenia, Bangladesh, Belarus, Belgium, China, France, India, Indonesia, Japan, Malaysia, Pakistan, Romania, the Russian Federation, Thailand, Ukraine, the United States of America and Viet Nam, who acted as participants or observers in different project tasks.

INPRO was established in 2000 to help ensure that nuclear energy is available to contribute to meeting the energy needs of the twenty-first century in a sustainable manner. It is a mechanism for INPRO members to collaborate on topics of joint interest. The results of INPRO's activities are made available to all IAEA Member States.

INPRO has introduced the concept of a sustainable nuclear energy system (NES) [1–3]. This concept is based on the United Nations definition of sustainable development [4] as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" which is categorized into nuclear specific technical and institutional areas by the INPRO methodology for NES assessment [3]. The INPRO Task 1, entitled Global Scenarios, has the objective to develop, based on scientific and technical analyses, global and regional nuclear energy scenarios leading to a global vision of sustainable nuclear energy in the twenty-first century. By developing those scenarios, INPRO helps both newcomers and existing nuclear countries to understand the key issues in a transition to future sustainable NESs and the role that innovations and collaboration among countries could play in such a transition.

Existing NESs, which are almost entirely based on thermal reactors operating in a once-through nuclear fuel cycle, will continue to be the main contributor to nuclear energy production for at least several more decades. However, the results of multiple national and international studies [1] show major enhancements of nuclear energy sustainability cannot be achieved without major innovations in reactor and nuclear fuel cycle technologies or without collaboration among countries.

New reactors, nuclear fuels and fuel cycle technologies are under development and demonstration worldwide. Combining different reactor types and associated fuel chains creates a multiplicity of NES arrangements potentially contributing to the global sustainability of nuclear energy. Cooperation among countries in the nuclear fuel cycle would be essential to bring sustainability benefits from innovations in technology to all interested users. In order to create viable cooperation among countries, it is becoming clear that national strategies will have to be harmonized with regional and global nuclear energy architectures to make national NESs more sustainable.

A number of INPRO collaborative projects have examined these issues over the last decade, building up to the enveloping project ROADMAPS. The project was implemented by experts nominated by several Member States representing countries with large, well established nuclear programmes that export reactors and conduct active research and development ('technology holder' countries), countries with smaller programmes not including export ('technology user' countries) and countries that do not yet have nuclear energy but are considering or are in the process of starting a nuclear programme ('newcomer' countries).

1.2. OBJECTIVE

The objective of this publication is to present the major outputs of the INPRO collaborative project ROADMAPS, which are as follows:

— A roadmap template representing a structured approach for globally enhancing nuclear energy sustainability, providing models for international cooperation and a framework for documenting actions, scope of work and timeframes for specific collaborative efforts by particular stakeholders;
— An approach for the bottom-up integration of national roadmaps to derive a regional or global projection of a pathway towards enhanced nuclear energy sustainability;
— The ROADMAPS tool (a Microsoft Excel spreadsheet, also called ROADMAPS-ET), which is a spreadsheet realization of the roadmap template that supports the practical application of the abovementioned approaches and the analysis and visualization of the results of such applications;
— Examples of a trial application of the roadmap template and the integration approach in a series of case studies performed by project participants.

This IAEA Nuclear Energy Series publication is intended for decision makers and technical experts from Member State institutions, nuclear industry and utilities, researchers and technical experts from universities and R&D institutions, working in the area of planning and implementation of a national nuclear power programme with provisions for cooperation with other countries.

1.3. SCOPE

This publication introduces the concept of roadmapping for enhanced nuclear energy sustainability, which has been developed over the course of several collaborative projects within INPRO and presents the outputs of the INPRO collaborative project ROADMAPS. The outputs are presented in line with the structure specified in Section 1.2. This publication focuses on sustainability issues associated with nuclear energy. The sustainability of non-nuclear energy systems was not within the scope of the ROADMAPS collaborative project.

The principal products of the ROADMAPS collaborative project are the roadmap template and the ROADMAPS-ET tool. ROADMAPS-ET is not a computational code but an analytical decision support tool for structuring, unifying and visualizing data on issues related to long term nuclear energy planning and NES sustainability enhancement. It is supplemented by an approach for the bottom-up integration of national roadmaps.

ROADMAPS-ET comprises 20 sheets in an Excel workbook for specifying various elements of a roadmap. The tool combines all these elements, following technical and practical logic, to help experts and decision makers understand the main issues related to enhancing the sustainability of nuclear energy. The outputs are visualized by means of Gantt charts showing key developments on a timeline and an implementation schedule of action items. Nuclear fuel cycle material flow information for the existing and future reactors and the associated fuel cycle front end and back end is included.

This publication includes case studies of trial applications of the roadmap template conducted by experts from Member States and IAEA staff members working on INPRO. The studies address national or cooperative long term nuclear energy deployment scenarios with evolutionary and innovative nuclear energy technologies. This publication also provides examples of possible roadmap aggregation for analysis at regional and global levels.

1.4. STRUCTURE

Section 2 presents the concept of roadmapping for enhanced nuclear energy sustainability, explaining its place among other INPRO activities, its content, its inputs and outputs and its possible applications in the near and longer term. It also provides an overview of previous studies on nuclear energy related roadmaps.

Section 3 introduces the roadmap template and gives guidance on its application. The points addressed are the purpose of the roadmap template and its structural components: general country information; national plans and prospects for nuclear energy development; metrics on nuclear energy position and development; key tasks and developments; the evolution of the reactor fleet and supply–demand balances for nuclear fuel cycle products and services; integration and cross-cutting analysis; progress monitoring; reactor database and information sources; and nuclear power planning and scenario analysis tools.

Section 4 documents the conclusions and recommendations of the ROADMAPS collaborative project.

The on-line supplementary files for this publication (Annexes I–IX, the user instructions and the ROADMAPS spreadsheet) can be found on the publication's individual web page at www.iaea.org/publications.

Annex I provides additional information on roadmapping, including background on different types of roadmaps used for nuclear technology and systems development. Annexes II–IV provide several country views on the role of innovations and international cooperation in national NESs, those being: a report from China on sustainability enhancement via an NES based on a closed fuel cycle and fast reactor technology in Annex II; a report from Japan on the commercialization of fast reactors and closed fuel cycles in Annex III; and a study from the Russian Federation on the potential of non-electrical applications of high temperature gas cooled reactors in Annex IV.

Annex V lists analytical and visualization tools for roadmapping. Annex VI explains the role of collaboration among countries in enhancing nuclear energy sustainability. Annex VII features discussions on roadmapping for a transition to globally sustainable nuclear energy held at the 11th INPRO Dialogue Forum in October 2015.

Annex VIII contains a number of case studies, which are trial applications of the roadmap template and the ROADMAPS-ET.

Case studies from Armenia (Section VIII.2) and Belarus (Section VIII.3) represent the standpoints of a country with a small electricity grid and a newcomer country, respectively. Both studies consider a once-through nuclear fuel cycle with water cooled thermal reactors for the period up to the end of the present century. Armenia and Belarus both need to collaborate with other countries on the construction of any nuclear power plants (NPPs) and on the sustainability issues of a once-through nuclear fuel cycle.

A trial case study from Romania (Section VIII.4) focuses on the needs and security of nuclear fuel supply, on operational performance indicators and on radioactive waste management, including waste disposal up to the year 2100. The study has identified a potential for international collaboration in fuel cycle activities envisaging the benefits for national NES development.

A trial case study from Thailand (Section VIII.5) presents an example of the roadmap template application for a newcomer country. The simplified roadmap visualization for a newcomer country was developed to provide an example of nuclear power planning and scenarios of a country up to the year 2100.

A trial case study from Ukraine (Section VIII.6) considered national demands for enrichment, long term spent nuclear fuel storage and nuclear fuel fabrication for the period up to the year 2100 with the goal of enhancing the sustainability of the national NES. The study identified possible gaps in achieving the sustainable development of the national NES based on a once-through nuclear fuel cycle with long term storage of spent nuclear fuel.

Annex IX presents examples of roadmap template application for regional or global analysis. In this study, the Russian Federation roadmap is integrated with roadmaps from Armenia, Belarus and Ukraine. The joint synergistic NES with thermal and fast reactors makes it possible to arrange a win–win cooperation for both the receiving and providing partners.

A study on the bottom-up aggregation of metrics (Section IX.2) presents an approach to the aggregation of the technology holder, technology user and newcomer countries' roadmaps for a regional and global analysis. This study is based on the questionnaire of the 11th INPRO Dialogue Forum Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems convened in 2015.

Section IX.3 presents a trial application of the roadmap template to the scenarios developed in the INPRO project Global Architecture of Innovative Nuclear Energy Systems based on Thermal and Fast Reactors including a Closed Fuel Cycle (GAINS), including scenarios for adopters of advanced fuel cycles, maintainers of current once-through fuel cycles and newcomer countries. The study identified savings in time and resources that could be achieved through the transition to more sustainable regional and global NESs.

A study on the application of the roadmap template to the global NES (Section IX.4) is an examination of the availability and sufficiency of the global nuclear fuel cycle infrastructure to support the global growth of nuclear power for the evolutionary deployment scenario.

Section IX.5 summarizes major observations of the fourth INPRO Dialogue Forum Drivers and Impediments for Regional Cooperation on the Way to Sustainable Nuclear Energy Systems convened in 2012.

The on-line supplementary files also contain the ROADMAPS-ET tool, user instruction on its application and some examples demonstrating the implementation of this tool.

The structure of this publication has been developed to facilitate easy access of particular sections of interest to particular groups of readers. Thus, Section 2 applies to a broad audience, including both decision makers and experts, as well as researchers and technical experts in research organizations. Section 3 appeals specifically to those researchers and technical experts who are considering performing a roadmapping themselves. It contains sufficient technical details to enable such an effort to be undertaken. The summary, conclusions and path forward presented in Section 4 have been crafted to appeal to all audiences.

Regarding the supplementary material, trial applications of the roadmap template in national (Annex VIII), regional (Annex VIII.7) and global (Annex IX.4 and IX.5) long term nuclear energy planning contain both summaries (condensed roadmaps) that could appeal to senior experts and decision makers, and detailed presentations that would be of interest to those technical experts who perform or plan to perform roadmapping themselves. In particular, Sections VIII.2, VIII.4 and VIII.6 present the results of roadmapping for technology user countries, Sections VIII.3 and VIII.5 for newcomer countries with a certain background in the nuclear domain, and Section VIII.7 for a technology holder country. Section VIII.7 also presents an example of regional roadmapping involving cooperation between a technology holder country, technology user countries and newcomer countries. This might be of particular interest to those decision makers and senior experts who are in charge of international cooperation within a national nuclear energy programme.

2. THE CONCEPT OF ROADMAPPING TOWARDS ENHANCED NUCLEAR ENERGY SUSTAINABILITY

2.1. INTRODUCTION

This section presents the concept of roadmapping for enhanced nuclear energy sustainability, which was developed over the course of several collaborative projects within the INPRO task global scenarios and culminated in the ROADMAPS collaborative project.

Section 2.2 introduces the concept of sustainability, including the United Nations general definition of sustainable development and how that definition has been applied to nuclear energy in the INPRO concept of a sustainable NES.

Section 2.3 introduces the concept of enhancing NES sustainability. Sustainability can be enhanced on the local, regional and global scales by implementing both innovations in technology and mutually beneficial collaborative solutions. The section provides a short overview of the previously completed and ongoing INPRO activities relevant to sustainability enhancement, including NES enhancement through cooperation between countries. The ROADMAPS project is the culmination of these activities.

Section 2.4 introduces roadmapping as an integrated strategic planning and coordination tool for NES sustainability enhancement.

It is important to note that this publication focuses on sustainability issues associated with nuclear energy. The sustainability of non-nuclear energy systems was not within the scope of the ROADMAPS collaborative project.

2.2. SUSTAINABILITY OF NUCLEAR ENERGY SYSTEMS

This section discusses the origin of the concept of sustainable development and how it has been applied by the IAEA to assess the sustainability of NESs.

2.2.1. Concept of sustainable development

In 1987, a report of the United Nations World Commission on Environment and Development [4] (often known as the Brundtland Report) defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. This statement indicates that sustainability can be achieved by limiting the consumption of rare or unreplaceable materials (e.g. fossil fuels) or by identifying the location of and means of economic extraction of additional such materials so that their availability for future generations is not diminished. It also indicates that the environmental impacts of development should be limited so as to not significantly impact future generations.

The Brundtland Report presented its comments on nuclear energy in chapter 7, section III. It stated that in the area of nuclear energy, the focus of sustainability and sustainable development is on solving certain well known problems (referred to as ‘key issues’) of institutional and technological significance. Seven key issues are identified and discussed in the Brundtland Report [4]:

— Proliferation risks;
— Economics;
— Health and environment risks;
— Nuclear accident risks;

— Radioactive waste disposal;
— Sufficiency of national and international institutions (with particular emphasis on intergenerational and transnational responsibilities);
— Public acceptability.

Since then, several significant events related to sustainable development have taken place; however, none of them has invalidated the definition given in the Brundtland Report.

The Rio+20 United Nations Conference on Environment and Development was held in Rio de Janeiro, Brazil in 2012. The conference issued a document subtitled The Future We Want [5], which specifies practical measures for implementing sustainable development. In particular, the document identified energy as one of seven areas that needs priority attention.

The publication [5] stressed the importance of energy supply in the development process: “We recognize the critical role that energy plays in the development process, as access to sustainable modern energy services contributes to poverty eradication, saves lives, improves health and helps provide for basic human needs.”

Following the Rio+20 conference, the international community established the High-level Political Forum on Sustainable Development, which is the main United Nations platform on sustainable development and has pursued achieving the goals of sustainable development. In the process of these efforts, countries have adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs) [6, 7].

The IAEA plays an active part in helping the international community achieve the 17 SDGs. It assists countries in the use of nuclear and isotopic techniques that contribute directly to attaining 9 of the 17 Goals. Additional details on the IAEA’s SDG related activities are available on the IAEA website [8]. SDGs 7, 9, 13 and 17 are specifically relevant to INPRO activities:

— SDG 7: Ensure access to affordable, reliable, sustainable and modern energy for all;
— SDG 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation;
— SDG 13: Take urgent action to combat climate change and its impacts;
— SDG 17: Strengthen the means of implementation and revitalize the global partnership for sustainable development.

Additionally, the IAEA held a Scientific Forum in 2016 on the topic of Nuclear Technology for the SDGs. During the Scientific Forum, panellists agreed that combating climate change would be difficult without the expansion of nuclear energy. They also emphasized the large scale demand for low carbon electricity and that nuclear power capacity had to be increased to meet this demand. It was highlighted that two principal SDGs are directly connected with nuclear energy, SDG 7 and SDG 13. Additional details on the Scientific Forum are available on the IAEA web site [8].

An IAEA publication on Nuclear Power and Sustainable Development [9] explored the possible contribution of nuclear energy to addressing the issues of sustainable development through a large selection of indicators and in connection with the SDGs across the economic, environmental and social dimensions.

2.2.2. Energy planning and sustainable development

Sustainability can be considered from four related but different viewpoints or dimensions: economic, environmental, social and institutional [4]. The key challenge for sustainable energy development is to address these four dimensions in a balanced way, taking advantage of their interactions and making relevant trade-offs whenever needed.

The economic dimension encompasses the requirements for strong and durable economic growth, such as preserving financial stability and a low and stable inflation rate. The key issues for sustainable energy supply are economic performance, energy consumption, energy intensities, and efficiency of energy distribution and use.

The environmental dimension requires eliminating or reducing negative externalities that are responsible for the depletion of natural resources and environmental degradation. The following topics can be considered within the environmental dimension: climate change, air pollution, water pollution, solid and radioactive waste, energy resources, land use and deforestation.

Social sustainability emphasizes the importance of equity among various population groups, adaptability to major demographic changes, stability in social and cultural systems, democratic participation in decision making, as well as other social issues. The main topics of interest within the social dimension are energy affordability, accessibility and disparity, employment generation, public participation in decision making, energy security, proliferation threat and the safety of the energy system.

The fourth dimension in attaining sustainability is the development of an institutional infrastructure, since appropriate legal and policy instruments are required to encourage and implement sustainable development. The institutional dimension includes the following topics: a national sustainable energy strategy, international cooperation on energy, energy legislation and a regulatory framework, energy science and technology and energy accident preparedness and response measures.

Countries differ with respect to energy demand, available technologies, financing options and preferences. Owing to differences in population size, geographical location and national preferences there is no general answer to the question of how to produce energy in the most efficient and cost effective way. Achieving sustainability basically calls for projects to keep a positive and stable trend in a long term period. Another required feature is flexibility, which characterizes countries’ ability to adapt under the influences of possible threats and future challenges. Energy analysis and planning helps to identify an adequate energy demand and supply strategy, which helps establish a strategic energy vision for a country.

The activities of INPRO are centred on the key concepts of global nuclear energy sustainability and the development of long range nuclear energy strategies, so that nuclear energy is and remains available to meet national energy needs. In cooperation with Member States, INPRO has defined the requirements for a sustainable NES consistent with the United Nations concept of sustainable development and the SDGs [3, 4]. Based on this concept, a three part test of any approach to sustainability and sustainable development was proposed within INPRO as follows:

- Current development should be fit for the purpose of meeting current needs with minimized environmental impacts and acceptable economics.
- Current research, design, and development 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.
- The approach to meeting current needs should not compromise the ability of future generations to meet their needs.

When nuclear energy is identified by a Member State as a desirable component of its future energy mix, an integrated and iterative approach could be applied to proceed from the general to the more specific via iteration. The iterative steps in this approach could be performing a sustainability assessment of the existing or targeted NES(s) or an analysis and comparative evaluation of the NES(s) and NES evolution scenarios leading to the selected target(s). Such assessments and evaluations would help raise the awareness of all issues associated with the development and deployment of nuclear energy, support the development of a national strategic plan for nuclear energy and determine whether the proposed NES(s) or NES evolution scenario would meet the sustainable development criteria. Synergistic cooperation with other countries can accelerate deployment and sustainability enhancements for an NES by avoiding the need to develop advanced technologies and deploy all parts of the NES indigenously.

2.2.3. INPRO methodology for the sustainability assessment of an NES

To address the important specific issues relevant to the development and deployment of an NES, INPRO has established a methodology for assessing NES sustainability [3, 10–13]. The INPRO methodology categorizes the four dimensions of the United Nations concept into six subject areas important for nuclear energy (slightly rearranging the original seven areas for nuclear energy from the Brundtland Report): economics, waste management, infrastructure, proliferation resistance, environment and safety. In each INPRO subject area, key issues of NES sustainable development are examined.

The structure of the methodology (see Fig. 1) is a hierarchy of INPRO basic principles, followed by user requirements, and criteria. In a given area of the INPRO methodology, a basic principle establishes a target or goal that needs to be achieved for the NES to be a sustainable energy system in the long term. User requirements relevant for a particular basic principle define what needs to be done to meet the target or goal of the basic principle and are directed at specific institutions (stakeholders) involved in nuclear power development and operation. The criteria and acceptance limits given for each user requirement are then used in a Nuclear Energy System Assessment (NESA) to determine whether the user requirements are met by a specific NES.

In total, the INPRO methodology incorporates 7 basic principles, 30 user requirements and more than 100 criteria in the defined assessment areas and considers the timeframe of assessment up to the end of the twenty-first century, with greater emphasis on the short and medium terms. An NES that meets all of the criteria is deemed to be sustainable. However, a more important function of the INPRO methodology is to identify gaps regarding NES sustainability. Such identification provides an important input for defining the strategy to support the development and deployment of a sustainable system or a component thereof.

The system of basic principles, user requirements and criteria in the INPRO methodology provides for detailed assessment of the sustainability of a well defined NES, but this level of detail makes it difficult to apply more generally for assessing sustainability trends in local, regional or global systems. However, the INPRO methodology also incorporates provisions for sustainability enhancement through the concept of key indicators by which substantial enhancements of sustainability and the associated risks in particular assessment areas can be evaluated and quantified. The 'key indicator' concept has not been used in nuclear energy system assessments performed on specific systems by Member States [14–16] but has found multiple applications in the activities carried out for the INPRO task Global Scenarios, as highlighted in the following sections.

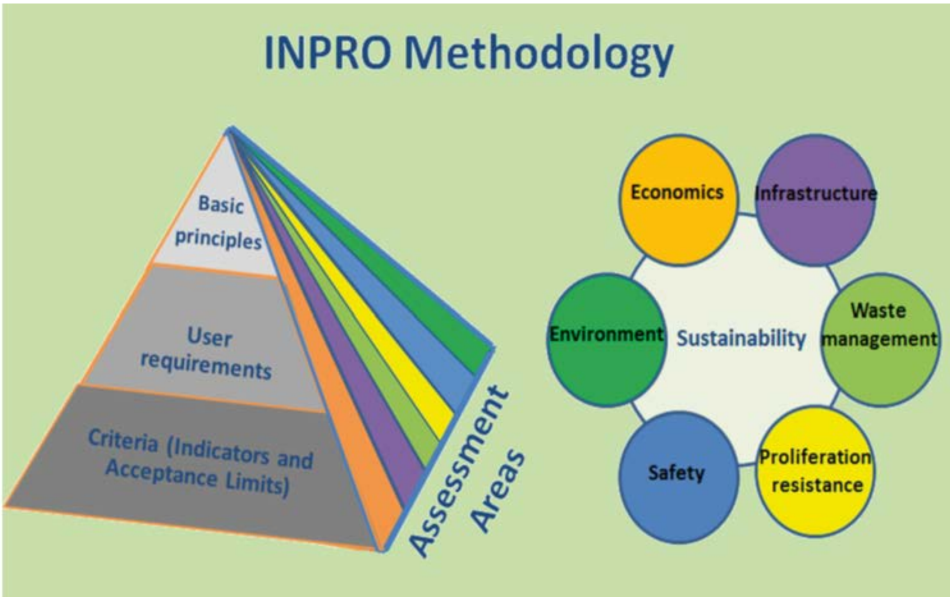


FIG. 1. Hierarchy of the INPRO methodology for NES sustainability assessment [3].

2.3. APPROACHES FOR NES SUSTAINABILITY ENHANCEMENT

This section discusses the recent history of activities within the IAEA's INPRO programme to assess methods and develop tools for the evaluation of current and future NESs and how they contribute to the enhancement of global nuclear energy sustainability. These activities have culminated in the ROADMAPS project, which provides a means to document NES planned deployments and operations and identify collaboration opportunities.

2.3.1. Analytical framework for the evaluation of a nuclear energy evolution scenario for sustainability

The focus of the activities within INPRO Task 1, Global Scenarios, involves how to enhance overall global NES sustainability. Global sustainability is enhanced not only when specific systems achieve initial sustainability but whenever current systems are improved, either prior to becoming sustainable or as part of continuing improvement after initial sustainability is achieved. When initial or further development of an NES is being considered, the following questions naturally arise:

- How to transition from the current situation to the targeted NES;
- How to evaluate different possible transition scenarios to targeted NESs.

To facilitate finding answers to these questions, within the INPRO task Global Scenarios the GAINS project developed an analytical framework for nuclear energy evolution scenario evaluation regarding sustainability [1]. This framework includes [17]:

- A common methodological approach, including basic principles, assumptions and boundary conditions;
- Scenarios for long term nuclear power evolution based on Member States' high and low estimates for nuclear power demand until 2050, and trend projections to the year 2100 based on projections of international energy organizations;
- A heterogeneous global model to capture countries' different policies regarding the nuclear fuel cycle and, specifically, its back end;
- Metrics and tools to assess the sustainability of scenarios for a dynamic NES, including a set of key indicators and evaluation parameters;
- An international database of best estimate characteristics of existing and future innovative nuclear reactors and associated nuclear fuel cycles for material flow analysis, which expands upon other IAEA databases and takes into account different preferences of Member States;
- Findings from an analysis of scenarios of a transition from present nuclear reactors and fuel cycles to future NES architectures with innovative technological and collaborative solutions.

The developed analytical framework provided the first application of the 'key indicator' concept suggested in the INPRO methodology [3], enabling the comparison of the sustainability of NES evolution scenarios. Based on a set of scenario specific key indicators in the areas of material flow, resources and wastes, demands and required infrastructure for the fuel cycle front end and back end services, and economics, different NES evolution scenarios could be then analysed and evaluated. The GAINS metrics build on the INPRO methodology for NES assessment, but in most cases, do not duplicate it. They are narrower and focus on the areas that are important for scenario analysis, that is those that can be evaluated through material flow and associated economic analysis. In this way, the analytical framework allows the consideration of the sustainability enhancement of targeted NES options against that defined by the INPRO methodology.

GAINS has applied the developed analytical framework to the analysis of global NES scenarios and identified several global NES architectures with enhanced NES sustainability [1]. To achieve this objective, the project developed a heterogeneous world model based on grouping countries with similar fuel cycle strategies, including technology holders in what it termed nuclear group 1 (NG1), technology users in nuclear group 2 (NG2) and newcomers in nuclear group 3 (NG3), as shown in Fig. 2. This model can facilitate a more realistic analysis of transition scenarios towards a global architecture of innovative NESs. It can also illustrate the global benefits that would result from some countries introducing innovative nuclear technologies, while limiting the exposure of the majority of countries to the financial risks and other burdens associated with the development and deployment of these technologies. GAINS has shown that enhanced sustainability may be difficult to achieve without broad cooperation between technology holder and technology user countries in the nuclear fuel cycle front end and back end.

The INPRO collaborative project Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES) has additionally verified the analytical framework and applied it to NES evolution scenarios involving regional (not necessarily geographically correlated) cooperation among countries [18].

SYNERGIES has developed a concept of options for enhanced nuclear energy sustainability, highlighted in brief in Section 2.3. According to it, enhanced sustainability may be achieved through improvements in technologies, changes in policies or both, as well as through enhanced cooperation among countries, including technology holder and technology user countries and internationally recognized bodies responsible for defining sustainable energy policy on a global scale.

An important message resulting from the GAINS collaborative project that has been carried forward through SYNERGIES into ROADMAPS is that each country will have its own policies relative to its NES, but different approaches provide opportunities (synergies) for collaboration whereby working together, countries can achieve their individual goals easier than when working alone, even if countries are not working towards the same goals or the same NES. In the GAINS and SYNERGIES projects it was also found that the key indicators can be used to track the evolution to enhanced sustainability, both at a country level and for a region or globally.

To support the practical applications of the developed analytical framework, especially for countries that do not have their own scenario analysis tools, the IAEA's MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts) has been adapted to model complex nuclear energy evolution scenarios involving different types of reactors and nuclear fuel cycle facilities in different countries and allowing modelling of different forms of cooperation among countries in the nuclear fuel cycle [19]. The adapted model, named MESSAGE-NES, has been verified through a series of case studies performed by experts in Member States [20]. The INPRO team provides Webex based training and consultations on the application of this tool. In addition to this, a database of best estimate economic data on reactors and nuclear fuel cycle steps has been compiled; it is available upon request from the IAEA.

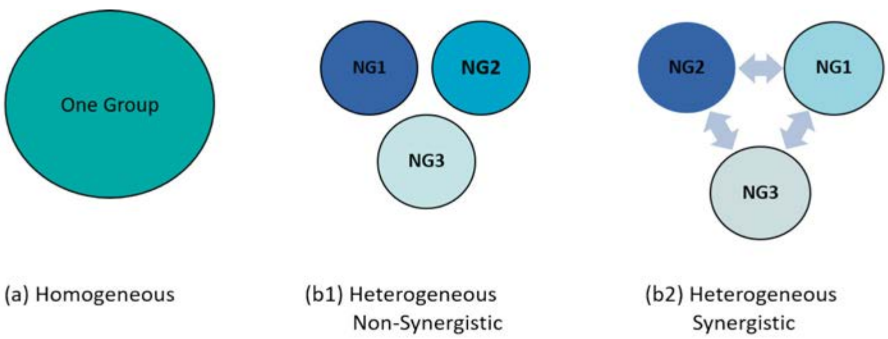


FIG. 2. Heterogeneous models for future global nuclear fuel cycle: (a) homogeneous world model where it is assumed that all countries pursue the same policy regarding nuclear fuel cycle, (b1) heterogeneous world model where countries pursue different policies regarding nuclear fuel cycle and do not cooperate with each other, (b2) heterogeneous world model where countries pursue different policies regarding nuclear fuel cuycle and cooperate with each other in a way that secures benefits for all) [17].

2.3.2. Comparative evaluation of NES options based on key indicators

The key indicator concept suggested by the INPRO methodology [3] and first applied in the GAINS collaborative project points to a possibility of the comparative evaluation of NES options or scenarios [21]. Such comparative evaluation is a planning tool and not a part of project implementation, which would require certain mandatory assessments, such as safety assessment or environmental impact assessment. Comparative evaluation allows the selection of an NES option that fits best for a particular user among those that comply or are assumed to comply with all regulatory requirements. The major issue in such comparative evaluation is that in a majority of real world challenges it would be impossible to find an NES option or scenario that would excel in all selected key indicators. The typical situation would be that some NES options or scenarios are better on some indicators, while others are better on other indicators.

To resolve the above mentioned issue, the INPRO collaborative project Key Indicators for Innovative Nuclear Energy Systems (KIND) has developed an approach to the comparative evaluation of NES options and scenarios based on the application of a set of selected key indicators, reflecting upon certain subject areas of the INPRO methodology, and a selected verified judgement aggregation (multicriteria decision analysis) and uncertainty analysis methods [21]. More specifically, the KIND project adapted and elaborated the state-of-the-art advanced methods of expert judgement aggregation for evaluations involving both quantifiable data and expert judgements, complete with the sensitivity and uncertainty analysis of methods of relevance. The approach to the comparative evaluation of NES options and scenarios developed within the KIND collaborative project includes the following main steps:

- Elaboration of a problem specific key indicator set;
- Determination of key indicator values for each of the NES options and scenarios under comparative evaluation (see Fig. 3) based on available (or calculated) data and on expert judgement (when data are not available or cannot be calculated);
- Selection of an appropriate multicriteria decision analysis method (typically, a multiattribute value theory) with expert and decision maker opinions based on the definition of weights and other parameters;
- Application of the KIND support tool to derive overall scores of options and specific scores at different levels of aggregation;
- Performance of sensitivity and uncertainty analysis;
- Presentation of results in visual form enabling the effective communication of the results to various interested parties including senior technical managers and policy decision makers.

The guidance and tools within the KIND project were initially developed for the comparative evaluation of the status, prospects, benefits and risks associated with the development of still immature innovative nuclear technologies for a more distant future. However, case studies on the trial application of the developed approach have shown its high potential for proposed solutions of other decision making support problems, such as comparative evaluations of nuclear energy evolution scenarios, comparative evaluation of evolutionary versus evolutionary, innovative versus evolutionary and even nuclear versus non-nuclear energy options.

The comparative evaluation approach of the KIND project is recommended for establishing a constructive dialogue between energy option proponents and decision makers regarding sustainable nuclear energy options. To support the practical applications of the developed approach to the comparative evaluation of NES options and scenarios, the KIND project has developed the KIND-ET tool [21], available upon request from the IAEA.

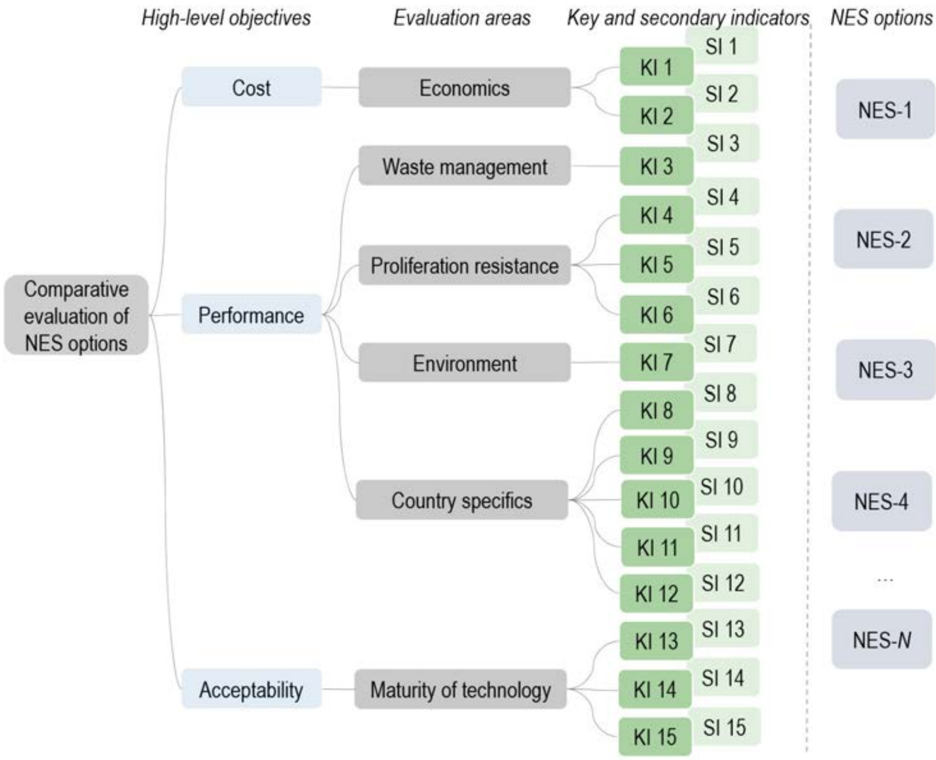


FIG. 3. Example of the KIND objectives tree [21].

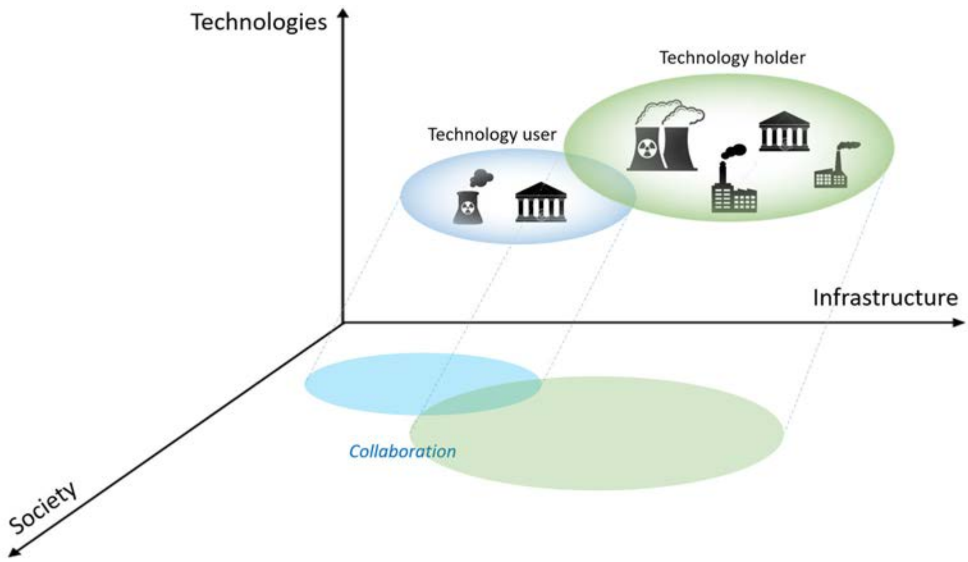


FIG. 4. The main dimensions of NES sustainability enhancement.

2.3.3. General considerations

Generically, nuclear energy sustainability can be enhanced via advanced reactors and fuel cycles, as well as via collaboration among countries. The directions of NES sustainability enhancement could be condensed in three main dimensions; see Fig. 4. Note that these dimensions include the four pillars of sustainability (economic, environment, social, institutional) discussed in Section 2.2.2:

- The technology dimension specifies a technological profile of national nuclear power: nuclear reactors and fuel cycle technologies, fissile material management strategies, spent nuclear fuel or high level waste (HLW) management policy, etc.
- The infrastructure dimension includes all components of hard (reactor and nuclear fuel cycle facilities, associated non-nuclear facilities, transport, etc.) and soft or institutional (legal nuclear framework, treaties and conventions, regulations, human resource, etc.) nuclear infrastructure.
- The social dimension comprises political, economic, social, environmental and development objectives of nuclear energy and related accomplishments, including the need for stakeholder involvement.

The preferences of countries regarding the sharing of resources between these dimensions are rather different. For instance, some countries are focused on fast economic growth and are going to use nuclear power to enable a rapid increase in energy consumption per capita. Some of these countries, especially nuclear energy newcomer countries, are focused on the import of nuclear energy technologies to minimize the necessary industrial nuclear fuel cycle infrastructure and establish legal infrastructure that would meet the requirements of international legislation.

Many countries with well developed nuclear technologies and infrastructure have already reached the main goals of energy saturation and their priorities for development are in the area of further enhancing living standards including ensuring all facets of social and environmental safety. These countries may be more focused on the technological and social dimensions to improve sustainability.

Eventually, each country determines their specific approach for providing the sustainability of their national NES based on public opinion and within the framework of international laws and agreements. The identification of specific features of a national position with respect to the status and plans for development of nuclear energy technologies, infrastructure and social context is a crucial point for examining potential means of NES sustainability enhancement.

The diversity of approaches for enhancing nuclear energy sustainability creates a basis for a mutually beneficial collaboration among countries based on complementary local conditions; see Fig. 4. Some established forms of partnership exist and are in the process of continuous development. Nowadays, cooperation plays a crucial role in the growth of world nuclear power and this role will be undoubtedly increased in the future.

2.3.4. Enhancing sustainability via technology innovations

Technological options for enhancing nuclear energy sustainability are presented in appendix V of Ref. [18]. They are structured by generic fuel cycle options, with generic reactor options linked to fuel cycle options. The reason for this is that generic reactor technologies may be common for several generic fuel cycle options, while generic fuel cycle options are limited in number and well known. Sections 2.3.4.1–2.3.4.6 present a short summary based on appendix V of Ref. [18].

2.3.4.1. Once-through nuclear fuel cycle

The once-through nuclear fuel cycle is currently the most widespread option realized in countries using nuclear energy. The reactors currently operated in a once-through nuclear fuel cycle include light water reactors (LWRs), gas cooled reactors (GCRs) and heavy water reactors (HWRs) but could include additional reactor types in the future, some of which could achieve high fuel burnup with savings in natural uranium consumption and a reduction in specific radioactive waste production.

2.3.4.2. Recycle of spent nuclear fuel with only physical processing

Another theoretical option is a single recycle of spent nuclear fuel from reactors of a particular type in nuclear reactors of another type, with no chemical reprocessing applied. This could help to a small extent to save natural uranium resources by using some of the remaining fissile material and reducing spent nuclear fuel volume for final disposal, while avoiding the use of proliferation sensitive chemical reprocessing technology. The technological readiness of such an approach is rated high; however, it has so far never been implemented in practice.

2.3.4.3. Limited recycling of spent nuclear fuel

A limited recycle of spent nuclear fuel includes chemical reprocessing and is a step towards improving resource utilization and reducing the waste burden. Limited recycle reduces spent nuclear fuel volumes, slightly improves resource utilization and keeps fertile fuel resources more accessible for later options of sustainability enhancement, thus offering some flexibility for the long term management of nuclear materials. This option is commercially realized as single mixed oxide (MOX) fuel recycle in LWRs.

2.3.4.4. Complete recycle of spent nuclear fuel

With the use of a closed nuclear fuel cycle and breeding of fissile material, all natural resources of fissile (^{235}U) and fertile (^{238}U) uranium and (^{232}Th) thorium could eventually be used through the conversion of all fertile nuclear materials into fissile with their subsequent fission. This enhancement option realizes a full utilization of the energy potential of nuclear fuel, improving uranium utilization by over two orders of magnitude, and enables a practical use of the larger thorium resources. It also reduces the long lived radiotoxicity burden of HLW by up to an order of magnitude, especially through keeping plutonium out of the waste. Within this option, both fast and thermal reactors of different types are being considered, such as sodium and heavy liquid metal cooled fast reactors, fast GCRs, LWRs, high-temperature gas-cooled reactor (HTGRs), molten salt and liquid (non-fuel) salt reactors.

2.3.4.5. Minor actinide or minor actinide and fission product transmutation

A closed nuclear fuel cycle with recycling of all actinides and final disposal of only fission products would provide the maximum benefits for combined resource utilization and waste hazard minimization. This enhancement option builds on the technologies of the previous options, providing some additional improvement in resource utilization and waste minimization when added to the complete recycle of spent nuclear fuel, but it adds costs that may impact the economics of energy generation. It also requires the development and deployment of minor actinide reprocessing or partitioning, minor-actinide-bearing fuels or targets and remote fuel or target fabrication technologies. A couple of decades ago, an option to also transmute long lived fission products was also being considered. As it was found that the long term radiotoxicity of long lived fission products is much less than that of the minor actinides, further research along this trend faded. The nuclear installations associated with this option may include commercial or dedicated fast reactors of different types, as well as accelerator driven systems and molten salt reactors.

2.3.4.6. Final geological disposal of all wastes

Final geological disposal of spent nuclear fuel or HLW applies to all the sustainability enhancement options mentioned above. To be sustainable, each generic fuel cycle option mentioned above should be amended by final geological disposal either of spent nuclear fuel, of some combinations of minor actinides and fission products, or of fission products only.

The possible timing for the introduction of different nuclear reactors and fuel cycles and for the expansion of nuclear energy markets has been discussed at the 11th INPRO Dialogue Forum. The output of these discussions is illustrated by Fig. 5. The reliable terms of commissioning and decommissioning of NES components are available only for NPPs of existing types, while the commissioning of new components of NES stems from projections based on long term strategies of nuclear power development in different countries. The latter are, of course, largely uncertain.

2.3.5. Collaborative enhancements

The sustainability benefits of nuclear technology and innovations in nuclear technology can be amplified through collaboration among technology holder and technology user countries (including newcomer countries). In particular, collaboration enables these benefits to be brought to those technology users who are not able or willing to deploy innovative technologies domestically.

Different studies performed within the GAINS [1] and SYNERGIES [18] projects at national and international levels have shown that a synergistic NES architecture based on technological and institutional innovations could provide the potential for a mutually beneficial collaboration between technology holders and users, facilitating nuclear energy production, resource preservation, waste and direct use material inventory reductions, and improving economics. Cooperation among technology holder and technology user countries would facilitate the deployment of the first NPP for newcomers and could secure a sustainability enhancement of many national NESs.

The potential benefits of cooperation among countries were a discussion topic at the fourth INPRO Dialogue Forum Drivers and Impediments for Regional Cooperation on the way to Sustainable Nuclear Energy Systems convened in 2012 with the broad representation of technology holder, technology user

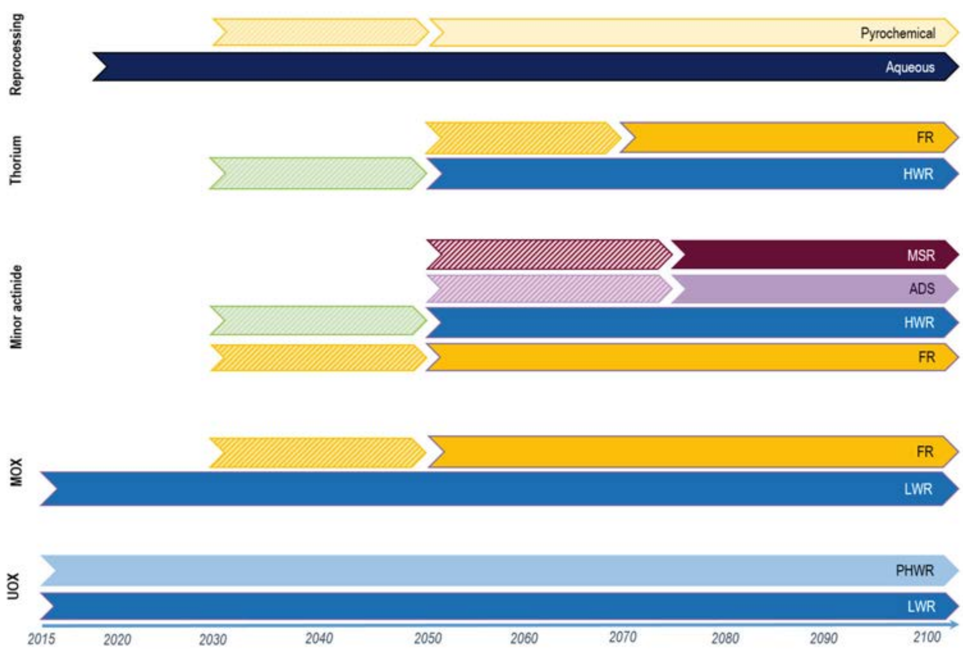


FIG. 5. Elements and transition points of nuclear technology evolution. The shaded arrows indicate limited availability (availability in only two or three countries) at commercial level at that time.

and newcomer countries. The findings of this forum were summarized in appendix IV of Ref. [18]. Among the benefits of cooperation mentioned by participants of the forum were:

- — Minimizing infrastructure effort for individual countries' NESs;
- — Suggesting sound solutions for spent nuclear fuel utilization and disposal;
- — Enabling optimum use of available resources;
- — Minimizing costs owing to the economy of scale and other factors;
- — Ensuring that international commitments are met by all countries in an easier and more transparent way.

However, the practical implementation of cooperation among countries is possible only when there are sound driving forces behind it that outweigh or help overcome the associated impediments. Options to enhance NES sustainability through cooperation among countries are analysed in detail in appendix V of Ref. [18]. Presented below is a brief summary of these options.

Nuclear trade and cooperation are significantly different from trade and cooperation in many other areas; they are more precisely regulated through agreements between countries. An 'agreement on peaceful nuclear cooperation' provides for more complex terms and responsibilities than those of agreements on trade in general in goods and services. Before any contract in nuclear trade is put in place, agreements between countries need to be concluded, which may be in the form of:

- — A bilateral agreement: This is an umbrella trade and cooperation agreement signed as a treaty between two trading partners describing the legal structure and obligations of the two parties. These can be quite complex and may include also third parties to the agreement.
- — Multiple bilateral agreements: Multiplicity is commonly viewed as a tool to emulate certain competitive market conditions in nuclear trade.
- — Multilateral agreements: A more rare agreement for cooperation on peaceful nuclear energy is an umbrella trade and cooperation agreement, signed as a treaty between a larger set of trading partners (could be a region), that creates a broader common understanding of nuclear trade and cooperation within a block of partner countries (e.g. EURATOM). These are much more complex to achieve also in terms of the time required.

Typically, a country may conclude one or several of these bilateral agreements depending on the needs of its industry for imports and exports of materials, equipment, services and intellectual property. This is the most common type of cooperation agreement. The multiple bilateral agreements provide for security of supplies to a State, but also commonly convey obligations, including those associated with safety, security and non-proliferation, to remain in compliance with the bilateral agreements. Beneath the bilateral agreements and subsequent arrangements are contracts that are required to comply with the terms of these legal trade instruments.

Ref. [18] mentions that:

> "If considered superficially, agreements governing international trade and cooperation on nuclear power and fuel cycle may seem to hamper competitive trade as found in less regulated markets. However, peaceful nuclear energy development and trade implies transfer of considerable and unique responsibilities and liabilities. The sophisticated nuclear trade regime helps to manage these specific and unique risks associated with nuclear energy development. … although rare, some examples of multilateral agreements (e.g. Treaty establishing the European Atomic Energy Community), as well as the emerging multiplicity of suppliers and bilateral agreements among certain countries (NPPs, fuel supplies and services) indicate that benefits of competitive trade can be achieved in the future for a variety of supplies in nuclear power and the nuclear fuel cycle, within the established governance models of international nuclear trade and cooperation."

Last but not least, preparing and signing agreements on nuclear cooperation may require changing national laws and carrying out sometimes lengthy negotiations with targeted partners; all this might take considerable time. In this context, projecting longer term perspectives of national nuclear power programmes could facilitate timely planning and implementation of the agreements necessary for competitive nuclear trade.

2.3.6. Collaboration in the development of infrastructure for newcomer countries

A wide range of infrastructure issues needs to be addressed before a country can introduce its first NPP. The necessary infrastructure includes the essential legal, regulatory, managerial, technological, human and industrial capacity to be established and maintained throughout the entire lifetime of the nuclear energy programme. The IAEA Milestones approach [22] provides guidance on establishing an adequate infrastructure for the first NPP for decision makers developing a national nuclear energy programme in the short term. The Milestones approach measures the maturity of the development of the infrastructure to support a nuclear energy programme. It involves governmental and implementing organizations that are engaged in the preparation for the deployment of the first NPP. The IAEA provides a service to Member States entitled Integrated Nuclear Infrastructure Review [23]. It is a part of the integrated services provided by the IAEA to Member States considering the initial development or expansion of their nuclear energy programmes. Integrated Nuclear Infrastructure Review covers 19 infrastructure issues to be considered at different stages of developing a national nuclear energy programme [22].

The INPRO methodology for NES sustainability assessment [10] takes a long term view of NES development and in its infrastructure basic principle sets the goal “that any country shall be able to adopt, maintain or enlarge an NES for the supply of energy and related products without making an excessive investment in national infrastructure”.

To minimize the effort needed for a nuclear infrastructure it is inter alia recommended that “the country is asked to use all available international and regional arrangements” [10]. Examples of such available arrangements are the World Nuclear University established with the support of the IAEA, contracts of the type ‘Build, Own, Operate’ and the fuel supply and take back arrangements offered by some suppliers of nuclear technology. As the relevant user requirement of the INPRO methodology puts it (UR6: Regional and international arrangements) [10]: “Regional and international arrangements should provide options that enable a country with an NES to minimize the infrastructure for a nuclear power programme.”

2.4. ROADMAPPING AS AN INTEGRATED APPROACH TO HELP MAINTAIN, ENHANCE AND MONITOR NES SUSTAINABILITY

This section provides a brief overview of roadmapping and its prior application to nuclear energy, then discusses the roadmapping approach used in the ROADMAPS project as a lead into detailed discussions on the roadmap template in Section 3. Annex I provides a longer version of this material.

2.4.1. General considerations for roadmapping

‘Roadmap’ is a generic term used as a synonym for ‘guide to future goals’, ‘guideline’, ‘plan’, ‘direction’, ‘instruction’, ‘map’, ‘protocol’, ‘standard’, ‘procedure’ [24]. Roadmapping is a target oriented planning process to help identify, select and develop alternatives to satisfy a set of certain requirements and provide information to make better decisions (technology or policy alternatives, R&D allocations, etc.) by identifying critical elements and gaps. A specific roadmap is a structured output of the roadmapping process including identified critical system elements (actions, technologies) and milestones (timeframes, time lags, interconnections) to meet performance targets and requirements (see Fig. 6).

There are many types of roadmaps related to the energy sector and, in particular, nuclear energy, depending on their focus. Some roadmaps are strategic plans focused on achieving a significant outcome such as CO_2 emissions reduction. Other roadmaps are focused on maturing a specific technology, such as a new type of nuclear reactor. Some are a combination of both types, especially when strategic goals require the use of new technologies, as is often the case in the energy sector.

Two examples of roadmaps are presented here. Figure 6 is a conceptual example of a multidisciplinary roadmap that shows how different layers of a business sector may interact over time to achieve goals such as bringing new products to market. Figure 7 is a specific example showing relative timeframes for demonstrating and deploying new nuclear technologies. Nuclear roadmaps can take many forms but they generally comprise multilayered time based diagrams that enable technological and institutional developments to be aligned with expected trends, drivers and impediments.

The application of roadmapping techniques to nuclear technologies is not new. Many national and international projects have been carried out that were related to the examination of diverse issues on the elaboration of nuclear technology related roadmaps using different analytical tools that had already found extensive applications in various subject areas. Within such studies, different issues were considered, from the elaboration of R&D roadmaps associated with a specific nuclear technology to the consideration of issues related to national NES deployment. These studies provide good illustrations of best practices that may serve as a pool of useful patterns, templates and frameworks exemplifying the main steps of the roadmap development process that are to be accomplished in roadmapping towards enhanced NES sustainability.

Annex I (which is an on-line supplementary file) provides an in-depth discussion on roadmapping, including descriptions and examples from a number of previous nuclear roadmapping studies and related multiple references.

2.4.2. Specifics of country level roadmapping for enhanced NES sustainability

As has already been noted, the ROADMAPS project has integrated the outputs of several other INPRO activities and developed a structure for globally enhancing the sustainability of nuclear energy, providing models for international cooperation and a framework for documenting actions, scope of work and timeframes for specific collaborative efforts by particular stakeholders. It has also developed a roadmap template and the ROADMAPS-ET that can be used in roadmapping studies. Roadmaps are usually top-down planning exercises that start with the major outcomes desired (visioning) and then

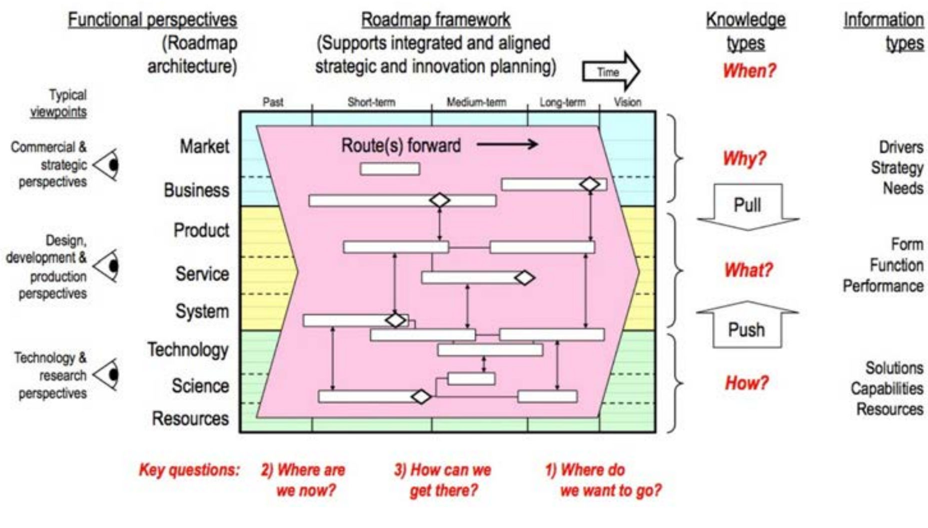


FIG. 6. Schematic multilayered roadmap, aligning multiple perspectives, highlighting fundamental generic strategic questions (reproduced from Ref. [25] with permission).

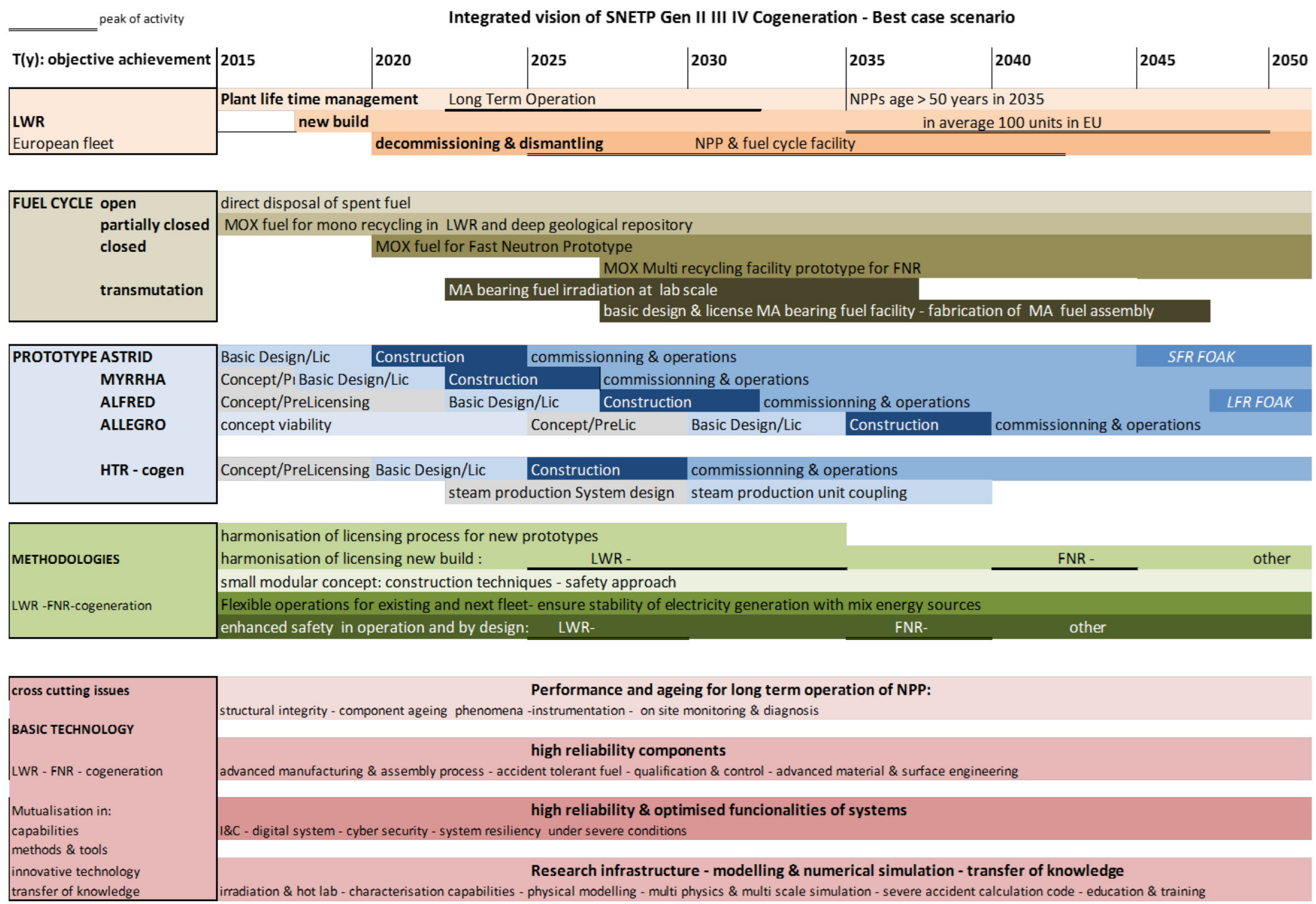


FIG. 7. The Sustainable Nuclear Energy Technology Platform deployment strategy (reproduced from Ref. [26]).

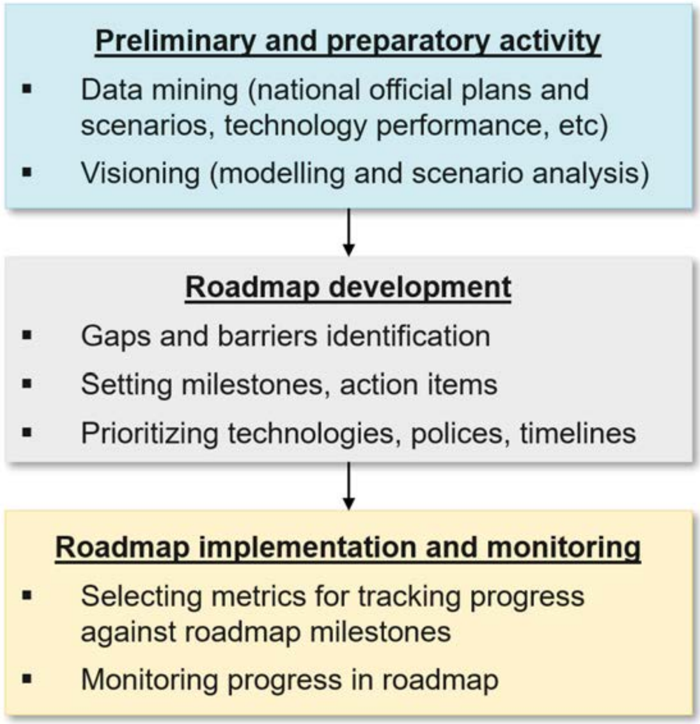


FIG. 8. General roadmapping flow chart.

work from the current state forward to identify pathways and milestones along those pathways to achieve those outcomes (roadmap elaboration) (Fig. 8). The roadmapping approach and tools developed in the ROADMAPS project enable individual countries to map out their nuclear energy futures, starting from the current state and working forward to show development in the near term (up to 2030), intermediate term (up to 2050) and long term (up to 2100) timeframes. The framework includes areas for presenting nuclear strategies related to technology development and collaboration and specific quantitative data on current and future reactors and fuel cycle facilities and associated flows of materials, including imports and exports.

Country level roadmaps can be used as stand-alone plans, but the relevant roadmapping toolkit also has to support the combination and linkage of multiple country level roadmaps into cooperative roadmaps, either for geographic regions or to model the current and projected interactions of trading partners. Harmonization of the roadmapping toolkit and the approaches elaborated within the INPRO activities in the areas of NES modelling and the comparative evaluation of NESs ensures effective coverage of the basic steps of roadmapping activities: visioning, roadmap elaboration and monitoring.

The dynamic nature of NES evolution needs to be adequately taken into account in roadmapping for a correct representation of national experts' and decision makers' preferences regarding NES assigned to different timeframes. It means that a set of goals, milestones and performance metrics need to be distributed over time, some of which may be more important within certain timeframes, but less important within the others.

In roadmapping studies, it is necessary to perform an identification of key gaps associated with a current NES and to establish a set of baselines for technological and collaborative sustainability enhancement options. It is also necessary to define principal milestones for prospective NES deployment. Based on these data, policy makers need to propose and justify additional measures to maintain or enhance sustainability, which would serve as a basis for experts to develop an action plan, that is, a roadmap identifying which kind of technological and collaborative options would need to be implemented when in order to meet the overall goal of NES sustainability enhancement.

2.4.3. Collaborative roadmapping to enhance nuclear energy sustainability

For the purpose of the ROADMAPS collaborative project, roadmapping is understood as developing long term nuclear energy planning for enhanced nuclear energy sustainability. When more than one country is involved, roadmapping needs to include a consideration of potential collaboration and associated synergies. Following the NES sustainability definitions of the INPRO methodology [3, 10–13] and the definitions of options to enhance nuclear energy sustainability from appendix V of Ref. [18], roadmapping targets nuclear energy sustainability enhanced through both technology innovation and cooperation among countries.

When developing collaborative roadmaps, both top-down and bottom-up approaches can be applied for the examination of the aggregated roadmaps that comprise several national NESs. A top-down approach begins with the shaping-up of a targeted aggregated NES with its subsequent breakdown into components — national NESs. A bottom-up approach is the piecing together of national NESs to give rise to a combined NES: national NESs as components of the aggregated NES are initially to be specified in detail and then combined together to arrive at a complete top-level NES. Apart from better reflecting the reality, where decisions on nuclear energy programmes are made by individual sovereign countries, the bottom-up approach in roadmapping towards enhanced nuclear energy sustainability allows specifying and analysing in detail the various possible mechanisms of collaboration among countries. On the contrary, in a top-down approach all collaborative nuances would inevitably appear hidden.

Roadmapping towards enhanced nuclear energy sustainability provides for addressing the timelines, technologies, institutional mechanisms and economic arrangements that support a collaborative enhancement of nuclear energy sustainability, as well as the drivers and impediments for such an enhancement. In this, the roadmap is assumed to indicate, inter alia, where savings in time, effort and resources could be achieved through collaboration with other countries.

Roadmapping is assumed to be based on a combination of official national plans (when available) in the short to medium terms and longer term projections based on national studies. As such, roadmapping would require periodic updates as plans are corrected and new studies on projections are performed and, therefore, would benefit from being established as a continuous process rather than a one-time effort.

Section 3 details the roadmap template developed by the ROADMAPS project to facilitate country level roadmapping and collaborative roadmapping.

3. THE ROADMAP TEMPLATE AND GUIDANCE FOR ITS APPLICATION

3.1. INTRODUCTION

When elaborating a roadmap towards enhanced nuclear energy sustainability at national, regional or global levels it becomes practical to acquire an appropriate analytical tool, which can detail and specify the actions to be taken by particular stakeholders, the scope of work, the technologies, the timeframes and the institutional and other cross-cutting mechanisms that could facilitate NES sustainability enhancement. Equally important is that the tool allows clear identification of the possible time and resource savings achievable through cooperation with other countries, as well as of drivers of and impediments to such cooperation and of other obstacles on the way to enhancing the sustainability of an NES. By evaluating the data in specific segments of such a tool it would be necessary to be able to conclude that a given NES configuration can or cannot contribute to sustainability enhancement. The results of such an evaluation would then provide an important input for defining the strategy and the necessary short, medium and long term R&D and institutional development plans to support the development and deployment of a targeted system or a component thereof.

Providing an appropriate qualitative visualization is very important as it is a characteristic feature of any roadmap to demonstrate interconnections, system evolutions and time dependencies etc. Overall, a roadmap will ideally be presented as a multilayered time based chart. Within NES oriented roadmapping, it is inter alia necessary to model the existing and planned (or projected) reactor fleet and the requirements for products and services of the nuclear fuel cycle front end and back end within the selected timeframes.

The roadmapping tool needs to provide for the analysis of a system's response to changes in the deployment strategy, for the identification of the associated direct and indirect effects and for the evaluation of the feasibility of certain options for NES development.

Overall, the roadmapping tool needs to support roadmap development and implementation, making it possible to explore linkages, trade-offs and consequences, thereby facilitating finding solutions consistent with the SDGs.

This section presents the concept of such an analytical tool developed within the ROADMAPS collaborative project, hereafter referred to as the 'roadmap template'. As a software tool, the roadmap template can be realized in different formats; within the ROADMAPS project it has been implemented in a spreadsheet format (ROADMAPS-ET).

3.2. PURPOSE OF THE ROADMAP TEMPLATE AND ITS STRUCTURE

The roadmap template can be used for strategic planning and analytical studies, as well as for the preparation of reports for managers and even articles for the media regarding issues related to the enhancement of NES sustainability.

The roadmap template includes several structural elements, interrelated by a common logic and allowing the characterization of the current situation in the nuclear energy sector and plans or projections for nuclear power development in the time perspective under consideration. The main structural components of the roadmap template are as follows:

— General country information;
— National plans and perspectives on nuclear energy development;
— Metrics on nuclear energy position and development;
— Key tasks and developments;
— Reactor fleet and nuclear fuel cycle evolution;
— Integration and cross-cutting analysis;
— Progress monitoring;
— Reactor database and information sources;
— Nuclear power planning and scenario analysis tools.

The roadmap template is designed as a flexible, multipurpose and easy-to-use analytical tool. It embraces all categories of nuclear stakeholders, including technology holders, technology users and newcomer countries. The template employs Gantt charts directly intended for the analysis of NES deployment strategies and for the presentation of the results of this analysis at national, regional and global levels. Although the template contains a tool that makes it possible, if necessary, to perform supporting calculations, the template overall is a qualitative analytical instrument, the main objective of which is to standardize and structure the information submissions on issues relevant for NES sustainability enhancement.

Among many possible visualization methods, Gantt charts are widespread and popular in roadmapping and other project management applications where project schedules need to be illustrated;

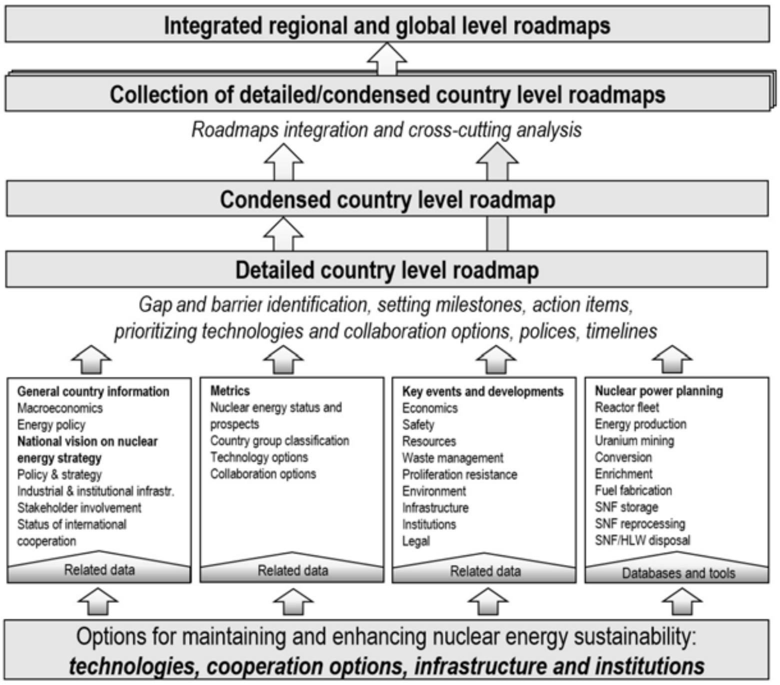


FIG. 9. Diagram of the roadmap template. Legend: SNF — spent nuclear fuel.

creating them can serve as one of the planning methods to reflect qualitative and quantitative information and data.

The roadmap template provides a concise, illustrative and interactive report on one or several screens. It represents a set of essential data and indicators grouped and arranged in such a way that all minimally necessary basic and key information is located on the same screen. This allows users to easily keep a track of key changes in the system and its conditions. The roadmap template is focused on visualizing the most essential data or indicators so that an expert could quickly obtain necessary information about any part of the process (e.g. the actual system state, performance metrics). The structure of the roadmap template is shown in Fig. 9. It consists of several sections and links between them. The template is intended for a country level roadmap. Several country level roadmaps can then be combined. The template is realized in the ROADMAPS-ET spreadsheet tool, which also enables certain data cross-cutting, processing and visualization.

3.3. COUNTRY NUCLEAR POWER PROFILE

3.3.1. General country information

The roadmap template realized in the ROADMAPS-ET spreadsheet tool is structured in sections corresponding to clickable icons in the bottom of the screen and blocks (of data) or worksheets for data input within each section.

The first section of the roadmap template is ‘Country profile’, which provides general information on the macroeconomic conditions and motivation for nuclear power deployment, strategy and development scenarios in the energy sector, nuclear energy as part of a national energy mix and the share of nuclear energy in the national energy mix. This information can be used to analyse the general situation of the country’s economy and to understand the prospects for further development or implementation of the country’s NES. Below are some examples of the blocks in this section.

The *‘General’* block (Fig. 10) can contain general information about the country of the template user. This information can be useful for understanding the maturity of the economy, the scale of needs for new generating capacities, market volumes and other economic aspects. It indicates the name of the country, the total population, gross domestic product (GDP) and GDP per capita.

The ‘Primary energy supply and demand’ block (Fig. 11 (a)) can present data on the total volume of the produced primary energy broken down by a type of fuel, import/export, production of primary energy per capita and by GDP. This block can also include information on primary energy demand by various sectors of the economy. These data indicate the share of nuclear power in energy balance of the country, and on what share of demand in which sectors of the economy it could be oriented.

The ‘Electricity and emissions’ block (Fig. 11 (b)) includes data on the total volume of supplied electric power, electricity generation capacity with a breakdown by fuel sources, import/export of electricity, consumed electricity per capita and by GDP, data on the volume of carbon emissions with a breakdown by sectors of economy and total emissions per capita and by GDP. These data support an overview of environmental characteristics of the main competitors of nuclear power in the electricity market and indicate the level of carbon emissions in various sectors of the economy. Thus, they reveal options and preconditions for an increase of nuclear power contribution to a reduction of greenhouse gas (GHG) emissions.

Country	
Year	
Population, mln	
GDP, bln USD	
GDP per capita, 10^3 USD/c	-

FIG. 10. Block with the ‘General’ data from the roadmap template.

Total Primary Energy Supply, Mtoe	
Coal	
Oil	
Natural gas	
Nuclear	
Hydro	
Renewables	
Energy imports	
Energy exports	
Energy supply per capita, toe/c	-
Energy supply per unit GDP, toe/10^3 USD	-

Energy Demand by Sector	
Industry	
Transportation	
Agriculture	
Commercial & public services	
Residential	
Non-energy use and other	

(a)

Total Electricity Supply, TWh	
Coal	
Oil	
Natural Gas	
Nuclear	
Hydro	
Renewables	
Imports	
Export	
Electricity supply per capita, MW·h/c	-
Electricity supply per unit GDP, kW·h/USD	-

CO_2 Emissions, Mt	
Industry	
Transport	
Non-energy use	
Others	
CO_2 emissions per capita, t/c	-
CO_2 emissions per unit GDP, t/10^3 USD	-

(b)

FIG. 11. The ‘Electricity and emissions’ block.

The data of relevance can be borrowed from annual reports of the government agencies and energy companies and from other publicly available sources. The aggregation of all data on one page seems reasonable, as it allows grasping immediately the general situation in the economy and the energy and nuclear energy sectors of the country. The section can include key political, economic, social, environmental and development objectives of the nuclear energy, the related accomplishments. It can also point to the needs for stakeholder involvement.

3.3.2. National plans and prospects for nuclear energy development

The roadmap template represents both national plans and the projections of nuclear energy evolutions over the period under consideration, which for INPRO is typically up to 2100. It includes the fundamentals of national decisions on nuclear power. Plans and projections need to comply with national nuclear energy strategy (if it exists) and with the country's general policy. They also need to comply with the country's commitment to proceed according to international obligations, norms and standards. Starting from the historical background of a national nuclear energy programme and NES, the roadmap template could reflect upon the following aspects:

— Nuclear energy policy and commitments to develop, implement and maintain a sustainable nuclear energy programme;
— A governmental nuclear energy strategy and industrial and the institutional infrastructure;
— Stakeholder involvement and the status of international cooperation in the nuclear sector;
— Possible scenarios and projections of long term nuclear energy development beyond the official plans;
— Institutional infrastructure: legal nuclear framework, international legal instruments (treaties, conventions, safeguards agreements etc.), regulatory framework, human resources and other relevant frameworks and instruments.

For newcomer countries the national plans need to outline the principle items of the national position. The national position here is understood as the outcome of a process that establishes the governmental strategy and commitment to develop, implement and maintain a sustainable nuclear energy programme.

The block 'Nuclear power' in section "Country profile" (Fig. 12) can include information on the current state of the country's nuclear energy programme. It provides data on the total installed capacity of the reactor fleet, the main types of reactors, data on the total capacities of the existing facilities at the various stages of the nuclear fuel cycle, available stocks of fissile materials (highly enriched uranium and plutonium) and the accumulated volumes of spent nuclear fuel with identification of spent fuel generation by different types of reactors (e.g. pressurized water reactor (PWR), HWR). The information provided in this block can be useful to identify possible areas for cooperation with other countries.

Annexes II–IV (which are on-line supplementary files) provide examples of a vision of a national nuclear energy strategy. Annex II explains the efforts of China in enhancing the sustainability of the national NES through implementing a closed nuclear fuel cycle and fast reactor programme including the construction of the China Experimental Fast Reactor, of the spent fuel reprocessing pilot plant, of the experimental facilities for reprocessing and of the experimental MOX fuel production line, and the R&D on fast reactor and accelerator driven system technologies and on a closed nuclear fuel cycle. Annex III reflects upon the efforts of Japan for the commercialization of FRs and a closed nuclear fuel cycle (the fast reactor fuel cycle). It includes the history of fast reactor cycle development, the scenario of the early commercialization of the fast reactor fuel cycle and a summary of the international collaboration in which Japan has been involved for fast reactor fuel cycle technology development. Annex IV presents a study of the potential for non-electrical applications of HTGRs in the roadmap for the development of nuclear energy of the Russian Federation.

Reactor Fleet, GW	
HWR	
PWR	
BWR	
AGR & GCR	
FR	
Others	
Nuclear Fuel Cycle Facilities, capacity	
Uranium mining and milling, t U	
Conversion, t U	
Enrichment, t SWU	
Fuel fabrication, t HM	
SNF storage, t HM	
SNF reprocessing, t HM	
SNF/HLW disposal, t HM	
Nuclear Fissile Material Stocks, t	
HEU	
Plutonium (civilian)	
Spent Nuclear Fuel, t HM	
HWR	
PWR	
BWR	
AGR & GCR	
FR	
Others	

FIG. 12. Block on the ‘Status of national nuclear power’. Legend: BWR — boiling water reactor; AGR — advanced GCR; FR — fast reactor; SNF — spent nuclear fuel; HEU — highly enriched uranium.

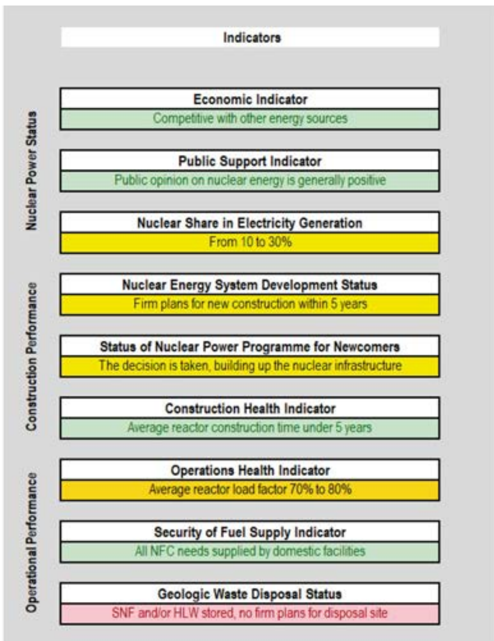


FIG. 13. Panel of Indicators. Legend: SNF — spent nuclear fuel.

3.3.3. Metrics for nuclear energy status and development

The roadmap template is a qualitative instrument for describing the current state of nuclear power in a country and the plans and/or projections for its further development. The main objective of the 'metrics' section is to reflect that every country is in its own particular situation. The metrics helps countries identify and understand areas where they have strong or weak sustainability. The metrics of individual countries could be aggregated and then the objective of such aggregated metrics would be to reveal the regional or global NES sustainability status.

The analytical information in the metrics section is divided into several blocks, each dedicated to a certain aspect of an NES. This set of blocks includes status indicators, prospects for nuclear energy size and growth, country group classification, technology options, domestic technology status and collaboration with other countries. The blocks qualitatively describe the current state of nuclear power in a country, the planned or projected growth and scale in the short, medium and long terms, the directions of nuclear fuel cycle development or the reliance on certain fuel cycle services available on international markets, the types of reactors, the types of fuel used, the availability of technologies for spent nuclear fuel reprocessing and/or facilities for spent nuclear fuel and HLW storage and disposal, the maturity status of all included technologies (research, prototype, demonstration, operating).

Particular attention needs to be paid to the description of cooperation (trade) with other countries and its scope. The variants of cooperation (trade) may inter alia include all stages of the nuclear fuel cycle, the purchase or sale of NPPs, the purchase or sale of services for the operation of NPPs and fuel cycle facilities and joint research programmes. The areas of cooperation (trade) need to be specified for the present moment, as well as for the short, medium and long terms.

The information in the metrics section, arranged in a single panel, facilitates grasping a qualitative picture of the current state of the national NES and of the prospects for its development, and points to options for cooperation (trade) with the country.

3.3.3.1. Status indicators

The block 'Indicators' includes a set of indicators describing different areas of a national NES. It is intended to give a general view of the current state of the NES. This block can be implemented using the colour coding technique (Fig. 13). The indicators in the considered areas would then have a colour gradation, for instance: green — excellent; yellow — good; orange — fair; red – poor; and colourless — this area is missing (there is no existing NES in the country). The considered areas are important for NES sustainability enhancement. Given below are some examples of signal indicators.

The economic indicator is an indicator qualitatively characterizing the current economic state of the NES. At present, economics plays a key role in the development of nuclear energy in countries. It has a significant impact on the decision to introduce nuclear energy in newcomer countries. Economic indicators for technology user and holder countries influence their decisions on the further expansion of their existing NESs, on NES stabilization and on nuclear share reduction up to the permanent shutdown of all NPPs. When providing information for this block, the choice of a certain indicator value needs to be based on detailed economic studies. The indicator values in the economic area can be competitive with other energy sources, competitive in most markets, competitive in limited markets, or can indicate a loss of competitiveness.

The public support indicator is an indicator qualitatively describing current public support for nuclear energy in a country. Similar to economics, public support has a strong impact on the prospects of the introduction or expansion of nuclear power. This indicator is especially important for newcomer countries. The indicator values in this area can be generally positive public opinion on nuclear energy, mixed/improving public opinion, mixed/declining public opinion and generally negative public opinion.

The nuclear share in electricity generation indicator is an indicator showing the nuclear share of electricity net generation. The indicator values can be not applicable, greater than 30%, from 10 to 30%, and less than 10%.

The NES development status indicator is an indicator qualitatively describing a country's attitude to the development of nuclear power. The presence of plants under construction or plans for NPP construction in the short term point to the active development of nuclear power in a country. At the same time, if a country has a large fleet of reactors and does not have any further plans for the construction of new NPPs, this may point to a decline of nuclear power in the future or to serious problems with replacement capacities. The indicator values can be not applicable, reactors currently under active construction, firm plans for new construction within the next 5 years, plans for new construction beyond the next 5 years, or no plans for new construction.

The status of nuclear power programme for newcomers indicator is an indicator to be applied by newcomer countries; it qualitatively describes the current state of a national nuclear energy programme in a country. The indicator values can be NPP under construction or commissioning, the decision to construct an NPP has been taken, national infrastructure for a nuclear power programme is being built, active feasibility studies under way or expressing interest in a national nuclear energy programme.

The construction health indicator (indicator of the construction status) is an indicator describing the average time of a new unit construction. The investment cost of an NPP has the largest share in the cost of kW·h of electricity from NPPs and strongly depends on the construction duration. A long construction duration or a delay in the construction of a new unit could lead to a loss of payback for NPPs in the future. The indicator values can be not applicable, average reactor construction time under 5 years, average reactor construction time under 6 years, average reactor construction time under 7 years or average reactor construction time over 7 years.

The operations health indicator is an indicator reflecting upon the efficiency of nuclear energy use in a country. The indicator values can be not applicable, average reactor load factor over 90%, average reactor load factor from 80% to 90%, average reactor load factor from 70% to 80% or average reactor load factor below 70%.

The security of fuel supply indicator characterizes the security of nuclear fuel supply in the country. The most favourable situation is when all needs (mining, conversion, enrichment, and fabrication) are covered by domestic facilities or can be obtained from several independent suppliers in other countries with whom bilateral agreements have been signed. The indicator values can be not applicable, all nuclear fuel cycle needs covered by domestic facilities, services from three or more independent suppliers secured, services from two independent suppliers secured, services only possible from one supplier (monopoly), or no confirmed fuel suppliers.

The geological disposal of waste status indicator characterizes the status of final geological disposal for spent nuclear fuel or HLW. At the time writing there was no demonstrated solution to the issue of the final geological disposal of waste. The indicator values can be not applicable, operating geological disposal facility for spent nuclear fuel and/or HLW, disposal facility under construction, site for disposal facility selected, spent nuclear fuel and/or HLW are being stored, or no firm plans for disposal site or facility.

3.3.3.2. Prospects for nuclear energy size and growth

The block 'Prospects for national nuclear energy size and growth' reflects upon national expectations regarding prospects for nuclear energy until the end of this century (Fig. 14). In the 'nuclear energy size' tab one of the following can be specified: no nuclear, small (0–10 GW(e)), medium (10–50 GW(e)) or large (>50 GW(e)). In the 'nuclear energy growth' tab the following can be specified[1]: decrease, stabilization considering replacement of units, small growth (below 0.1 GW(e)/year), medium growth (between 0.1 and 0.5 GW(e)/year) or significant growth (>0.5 GW(e)/year). Official plans of a country can be displayed as ☑, while projections or non-official plans can be displayed as ✓. The options need to be provided for four time ranges: current year (c.y.), short term (c.y.–2030), medium term (2031–2050) and long term (2051–2100).

[1] All inputs here should be provided taking into account permanent shutdowns of aged units.

3.3.3.3. Country group classification

Two country group classifications are provided for (Fig. 15). On one side (General classification), the inputs can be [technology] holder, [technology] user or newcomer. On another side (GAINS classification) the classification suggested in the INPRO collaborative project GAINS is applied.

The GAINS classification groups countries on a non-geographical basis according to their strategies regarding the nuclear fuel cycle (Fig. 16). Within it, each country is assigned to one of three country groups: NG1, NG2 or NG3. The definitions of the groups are as follows:

— NG1: This group of countries pursues FRs and a closed nuclear fuel cycle with reprocessing and recycling of spent nuclear fuel.
— NG2: This group of countries pursues a strategy either of spent nuclear fuel direct disposal or of sending the spent nuclear fuel abroad for reprocessing.
— NG3: The general strategy of this group of countries is to use fresh fuel supplied from abroad and to send the spent nuclear fuel abroad for either reprocessing or final disposal.

The country groups NG1, NG2 and NG3 can cooperate in the nuclear fuel cycle back end (the so-called synergistic case presented in Fig. 16 (b)) or no such cooperation can be present (the non-synergistic case presented in Fig. 16 (a)).

Nuclear Energy Growth

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Decreasing				
Stabilization	☑			
Small growth (below 0.1 GWe/year)		✓		
Medium growth (0.1 - 0.5 GWe/year)				
Significant growth (>0.5 GWe/year)				

Nuclear Energy Size

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
No nuclear				
Small (0-10 GWe)	☑			
Medium (10-50 GWe)		✓		
Large(>50 GWe)				

FIG. 14. 'Prospects for nuclear energy size and growth' block.

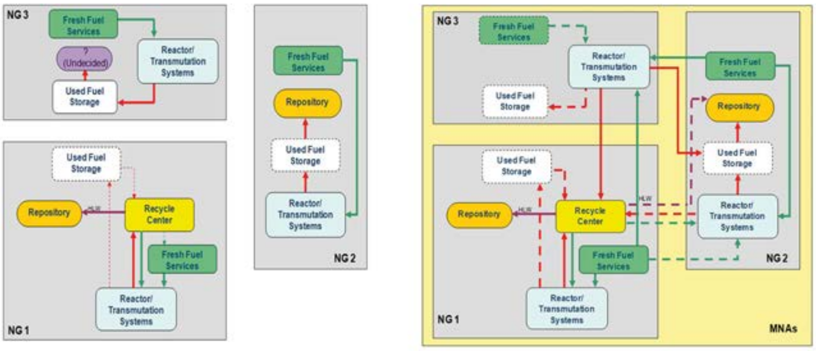
General Classification

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Holder		✓		
User	☑			
Newcomer				

GAINS Classification

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
NG1				
NG2		✓		
NG3	☑			

FIG. 15. 'Country group classification' block.



(a) *(b)*

FIG. 16. Country grouping used in GAINS [15].

3.3.3.4. Technology options and domestic technology status

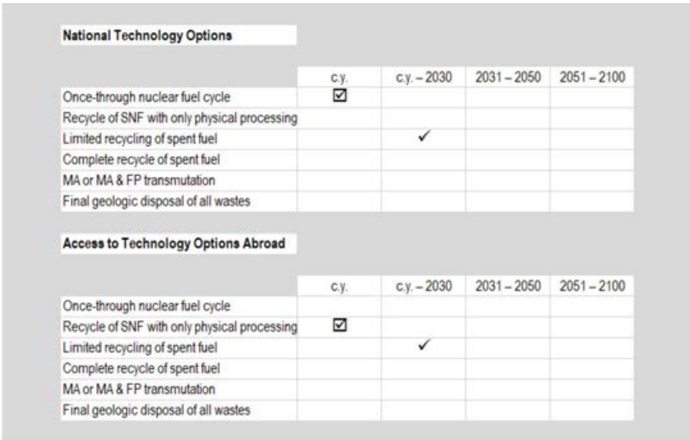
The block ‘technology options and domestic technology status’ specifies the technology options available domestically (indigenously) and those to which the country has access from abroad (Fig. 17). Several options can be specified simultaneously. The options need to be provided for four time ranges: the current, short, medium and long terms. The technology options themselves are identical both for the ‘national’ and ‘abroad’ cases and can include the following items:

— Once-through nuclear fuel cycle;
— Recycle of spent nuclear fuel with only physical reprocessing;
— Limited recycling of spent nuclear fuel;
— Complete recycle of spent nuclear fuel;
— Minor actinide or minor actinide and fission product transmutation;
— Final geological disposal of all wastes.

The block ‘domestic technology status’ includes four identical subsections to specify actual and expected national technological capabilities within the specific timeframes (current, short term, medium term or long term) with the identification of their status (research, prototype, demonstration or operating) (Fig. 18). The following options are included:

— LWR;
— HWR;
— High temperature GCR;
— Small modular reactor;
— Fast reactor;
— Accelerator driven system;
— Molten salt reactor;
— Uranium mining and milling;
— Conversion;
— Enrichment;
— Uranium fuel fabrication;
— Mixed uranium–plutonium fuel fabrication;
— Advanced type fuel fabrication;
— Wet spent nuclear fuel storage;

— Dry spent nuclear fuel storage;
— Aqueous spent nuclear fuel reprocessing;
— Advanced spent nuclear fuel reprocessing;
— HLW forms;
— Geological disposal of spent nuclear fuel and/or HLW;
— Related industrial activities;
— Others.



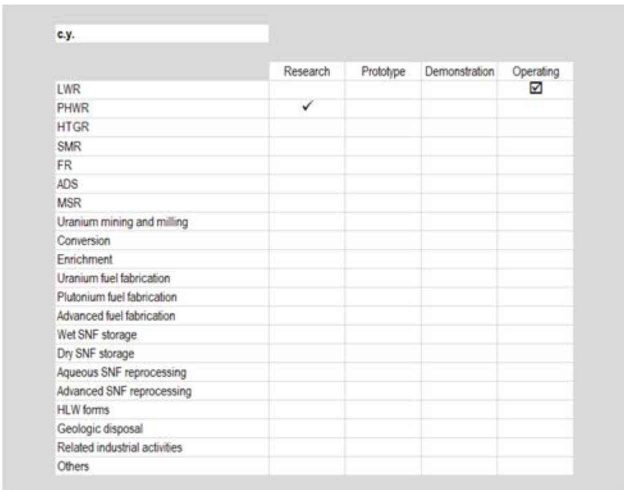
National Technology Options

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Once-through nuclear fuel cycle	☑			
Recycle of SNF with only physical processing				
Limited recycling of spent fuel		✓		
Complete recycle of spent fuel				
MA or MA & FP transmutation				
Final geologic disposal of all wastes				

Access to Technology Options Abroad

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Once-through nuclear fuel cycle				
Recycle of SNF with only physical processing	☑			
Limited recycling of spent fuel		✓		
Complete recycle of spent fuel				
MA or MA & FP transmutation				
Final geologic disposal of all wastes				

FIG. 17. ‘Technology options’ block. Legend: MA — minor actinide; FP — fission product.



c.y.

	Research	Prototype	Demonstration	Operating
LWR				☑
PHWR	✓			
HTGR				
SMR				
FR				
ADS				
MSR				
Uranium mining and milling				
Conversion				
Enrichment				
Uranium fuel fabrication				
Plutonium fuel fabrication				
Advanced fuel fabrication				
Wet SNF storage				
Dry SNF storage				
Aqueous SNF reprocessing				
Advanced SNF reprocessing				
HLW forms				
Geologic disposal				
Related industrial activities				
Others				

FIG. 18. Part of the ’Domestic technology status’ block. Legend: SMR — small and medium sized reactor; FR — fast reactor; ADS — accelerator driven system; SNF — spent nuclear fuel.

3.3.3.5. *Collaboration with other countries and collaboration agreements*

The block ‘Collaboration with other countries’ allows the user to specify a country’s cooperation with other countries, including nuclear trade, by marking areas in which such cooperation is ongoing or being planned or projected for the different timeframes (current, short term, medium term and long term) (Fig. 19). The following options are included in the table:

— Participate in information exchange activities;
— Joint R&D programmes;
— Sharing of R&D facilities;
— Collaboration on nuclear fuel cycle front end;
— NPP selling;
— NPP purchasing;
— Offer NPP operations services;
— Use NPP operations services;
— Offer NPP refuelling outage services;
— Use NPP refuelling outage services;
— Collaboration in nuclear fuel cycle international centres;
— Share an NPP with another country;
— Offer nuclear fuel cycle back end services;
— Use nuclear fuel cycle back end services;
— Offer nuclear fuel cycle full services;
— Use nuclear fuel cycle full services.

The block ‘Collaboration agreements’ is to specify under which agreements certain activities of a country are performed. The agreements included are: national, bilateral agreement with other country, multilateral agreement among several countries, and multiple bilateral agreements with other countries. (Fig. 20). Similar to the blocks ‘Technology options…’ and ‘collaboration with other countries’ the inputs need to be provided for four timeframes. The list of activities for which collaboration agreements need to be specified includes:

— Produce or offer uranium;
— Obtain uranium;
— Produce or offer converted uranium;
— Obtain converted uranium;
— Produce or offer enriched uranium;
— Obtain enriched uranium;
— Fabricate or offer fuel;
— Obtain fuel fabrication service;
— Produce or offer NPP design;
— Use NPP design service;
— Offer NPP operation service;
— Use NPP operation service;
— National spent nuclear fuel storage or offer spent nuclear fuel storage service;
— Use spent nuclear fuel storage service;
— National reprocessing or offer spent nuclear fuel reprocessing service;
— Use spent nuclear fuel reprocessing service;
— National disposal or offer spent nuclear fuel disposal service;
— Use spent nuclear fuel disposal service;
— National HLW disposal or offer HLW disposal service;
— Use HLW disposal service;
— Others.

Collaboration Strategy

	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
Participate in information exchange activities	☑			
Joint R&D programmes		☑		
Sharing of R&D facilities				
Collaboration on NFC front end			✓	
NPP selling				
NPP purchasing				
Offer NPP operations services				
Use NPP operations services				
Offer NPP refuelling outage services				
Use NPP refuelling outage services				
Collaboration on NFC international centres				✓
Share an NPP with another country				
Offer NFC back end services				
Use NFC back end services				
Offer NFC full services				
Use NFC full services				

FIG. 19. The 'Collaboration with other countries' block.

c.y.

	National	Bi-lateral	Multi-lateral	Multiple bi-lateral
Produce/Offer uranium	☑			
Obtain uranium		☑		
Produce/Offer converted uranium			✓	
Obtain converted uranium				
Produce/Offer enriched uranium				✓
Obtain enriched uranium				
Fabricate/Offer fuel				
Obtain fuel fabrication service				
Produce/Offer NPP design				
Use NPP design service				
Offer NPP operation service				
Use NPP operation service				
National SNF storage/Offer SNF storage service				
Use SNF storage service				
National reprocessing/Offer SNF reprocessing service				
Use SNF reprocessing service				
National disposal/Offer SNF disposal service				
Use SNF disposal service				
National HLW disposal/Offer HLW disposal service				
Use HLW disposal service				
Others				

FIG. 20. Part of the 'Collaboration agreements' block (data should not be entered in the shaded cells).

3.4. KEY TASKS AND DEVELOPMENTS TO ENHANCE NES SUSTAINABILITY

3.4.1. Timelines and forks towards enhanced NES sustainability

The national vision on NES development beyond the official plan can be represented by different future scenarios. For example, for many countries the selection of a variant on the final disposal of nuclear waste from among two or more alternatives is under consideration. In this case, there is a fork in a country roadmap that needs to be presented as respective variants.

The development of technological, infrastructural and institutional areas along with the development of collaborative mechanisms gives an opportunity to enhance sustainability by achieving the desirable targets in a stepwise manner, for example, set out in each subject area of the INPRO methodology for NES sustainability assessment. These subject areas are economics, environment and resources, safety, waste management, proliferation resistance, infrastructure including security, policy and public acceptance.

Forks in roadmaps indicate the need for performing a comparative evaluation or prioritizing relevant options that can be carried out using the approach to comparative evaluation of NES options or scenarios developed in the collaborative project KIND [21] that allow the definition of more promising options for achieving the selected targets.

Non-official plans and unknown plans need to be defined in the timelines indicating key developments and events, as well as in official plans. Projections could be based on the continuation of official plans but, if current plans may not be continued, it is better to indicate that plans are undetermined or undefined.

Timelines and forks can be presented in roadmaps by different means. Gantt charts are an option for timeline based presentation as they are widely used in project management applications to illustrate project schedules. Different elements of the Gantt charts can be used to clarify transition points, decision points and correlations between scenarios, for example. The same elements can be used for the development of condensed roadmaps (see Section 3.5.3).

Figure 21 provides an example of Gantt chart based presentation of the timelines and forks for the global GAINS scenarios from Ref. [1]. The GAINS project analysed a business-as-usual scenario (BAU) based on thermal reactors in a once-through nuclear fuel cycle and a scenario with a closed nuclear fuel cycle based on thermal and fast reactors (FRs); this is abbreviated as a BAU+FR scenario. From Fig. 21 it can be seen that the introduction of FRs into an NES necessitates plutonium based fuel fabrication, spent nuclear fuel reprocessing and final disposal of HLW only. Figure 22 explains different symbols that can be used to indicate the nature of the fork.

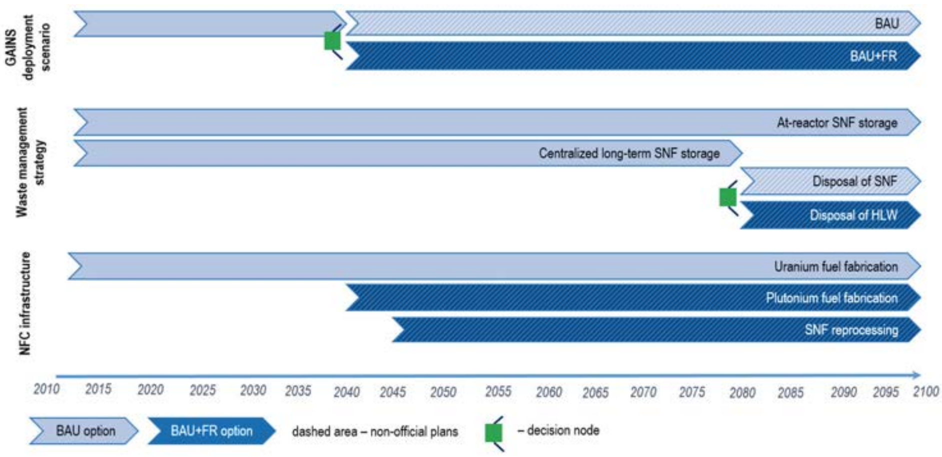


FIG. 21. Example of technological fork presentation for a roadmap based on GAINS scenarios.

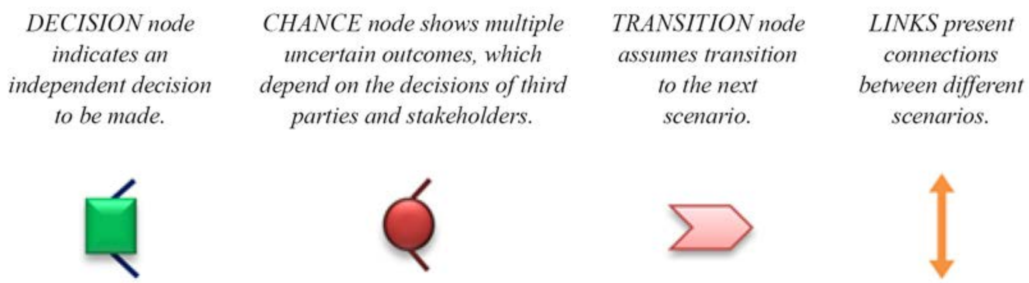


FIG. 22. Different symbols used to indicate the nature of the fork..

3.4.2. Presentation of key tasks and developments

Key tasks and developments, the implementation of which contributes to enhanced NES sustainability, are specified in the roadmap template using Gantt charts for different time intervals. The specification is to be performed in the ROADMAPS-ET section titled “Key tasks and developments”. The key tasks and developments can include commissioning of the new types of reactors and nuclear fuel cycle facilities supporting NES sustainability enhancement.

For newcomer countries it would be important to reflect the progression of tasks and developments related to the introduction of nuclear power, first of all, to the development of a national infrastructure for nuclear power, including the adoption of basic laws and regulations in the field of nuclear power. However, in a roadmap towards enhanced nuclear energy sustainability it will be not less important to specify the targeted construction and commissioning dates for the first and subsequent units, the types of NPPs to be constructed in different timeframes with corresponding nuclear fuel cycle requirements, the timelines for the conclusion of agreements with other countries that are suppliers of NPPs, nuclear fuel, fuel cycle services and possible solutions for the progressive spent nuclear fuel accumulation. When identifying key developments and tasks, the following may be considered:

- Different Member States can pursue and implement different strategies.
- The IAEA is not in a position to recommend or promote any specific strategy.
- A number of countries are developing closed nuclear fuel cycles for operation with fast and thermal reactors to meet the objectives of waste minimization and extended fissile resource availability.
- Other countries pursue alternative innovative nuclear technologies that might eventually help achieve enhanced sustainability benefits within a once-through nuclear fuel cycle.
- Cooperation among countries is considered by many Member States to be a vital tool for enhancing sustainability of their national NESs.

A non-binding example of setting the key tasks and developments is provided in the list of bullets below, based on a set of six areas important for NES sustainability. Each area contains several key developments, the achievement of which enhances the sustainability of an NES in the corresponding area.

(a) Economics:
   (i) Increased cost of electricity generated by nuclear power in the phase of the introduction of innovative technologies.
   (ii) The cost of electricity generated by nuclear power is comparable with wind, solar and other renewable energy sources being used for ensuring energy security, for diversification of energy sources or for decreasing adverse environmental impacts.
   (iii) The cost of electricity generated by nuclear power is at the level of the average cost in the electricity market.
   (iv) The cost of electricity generated by nuclear power shows the best economic performance in the energy sector.
(b) Safety:
   (i) Compliance with current regulations and the IAEA safety standards;
   (ii) Compliance with the requirements for the Generation III+ reactors;
   (iii) Compliance with the requirements for the Generation IV reactors.
(c) Resources:
   (i) Once-through nuclear fuel cycle with less than 1% of natural uranium being utilized;
   (ii) Utilization of depleted uranium or single recycle of plutonium based fuel;
   (iii) NES based on thermal and FRs with multiple recycling of plutonium;
   (iv) Full use of the energy potential of all fissile and fertile materials.
(d) Waste management:
   (i) Spent nuclear fuel storage in repositories on the NPP site;

    (ii) Centralized long term spent nuclear fuel storage;
    (iii) Final geological disposal of spent nuclear fuel or final geological disposal of HLW without actinides (uranium, plutonium and minor actinides).
(e) Non-proliferation and nuclear security:
    (i) Compliance with basic international and national commitments, obligations and policies regarding non-proliferation and nuclear security;
    (ii) Compliance with all international and national commitments, obligations and policies regarding non-proliferation and nuclear security;
    (iii) Balance of the production and consumption of fissile materials in the nuclear fuel cycle is secured by NES architecture.
(f) Public acceptance:
    (i) Lack of public and governmental support for nuclear energy;
    (ii) Public debate on the role of nuclear energy and pathways for its development;
    (iii) Positive attitude of the majority of the population and government to nuclear energy;
    (iv) Full support of a national nuclear energy programme from the population and government.

Figure 23 provides an example of how key events and developments for a hypothetical example could be presented in the roadmap template.

3.5. INPUT ON REACTOR FLEET AND RELEVANT NUCLEAR FUEL CYCLE FACILITIES

Several sections representing nuclear reactor fleet and relevant nuclear fuel cycle facilities form the core of the roadmap template. They directly respond to the main roadmapping objective, which is to develop a structured approach for enhancing the sustainability of nuclear energy globally, providing models for international cooperation and a framework for documenting actions, scope of work and timeframes for specific collaborative efforts by particular stakeholders.

The inputs in these sections make it possible to perform a material flow analysis to evaluate the supply and demand requirements in all stages of the nuclear fuel cycle. In turn, this makes it possible to evaluate the sufficiency of the existing and projected production capacities for nuclear reactors and nuclear fuel cycle facilities.

This goup of sections of the roadmap template incorporates the sections on reactor fleet and energy production, specifying the total installed capacities and energy production of a considered reactor fleet; the sections on uranium mining and milling; conversion; enrichment; fuel fabrication; spent fuel storage; spent fuel reprocessing; and geological disposal of spent fuel or HLW.

To provide for some flexibility in specifying the reactor park and relevant nuclear fuel cycle facilities or requirements the roadmap template makes it possible to select among several sets of the assumptions to take into account changes in the parameters over time (increase or decrease in fuel enrichment requirements, annual loading into the reactors, involvement of fissile materials from stocks etc.) and to consider the parameters specific to certain systems (e.g. the accumulation and consumption of plutonium in a closed nuclear fuel cycle). The specification of the main model assumptions is the area of responsibility of an expert elaborating the roadmap. The number of time periods and their duration need to be specified by the user and implemented consistently within all sections. The number of reactor types and their aggregation in groups also need to be specified by the user. The NPPs may include single or multiple reactor units. For convenience, reactor type can be specified individually for each unit, or a generalized reactor type can be specified, or a group of reactor types can be specified. Once the model assumptions are fixed, they are to be used within the whole process of roadmap development. If the intention is to create an aggregated roadmap, the same assumptions need to be selected and implemented for all roadmaps that will be integrated.

The data required to populate thesesections can be based on data from vendors or from a reliable information source, or it can be evaluated using nuclear fuel cycle material flow calculators or software

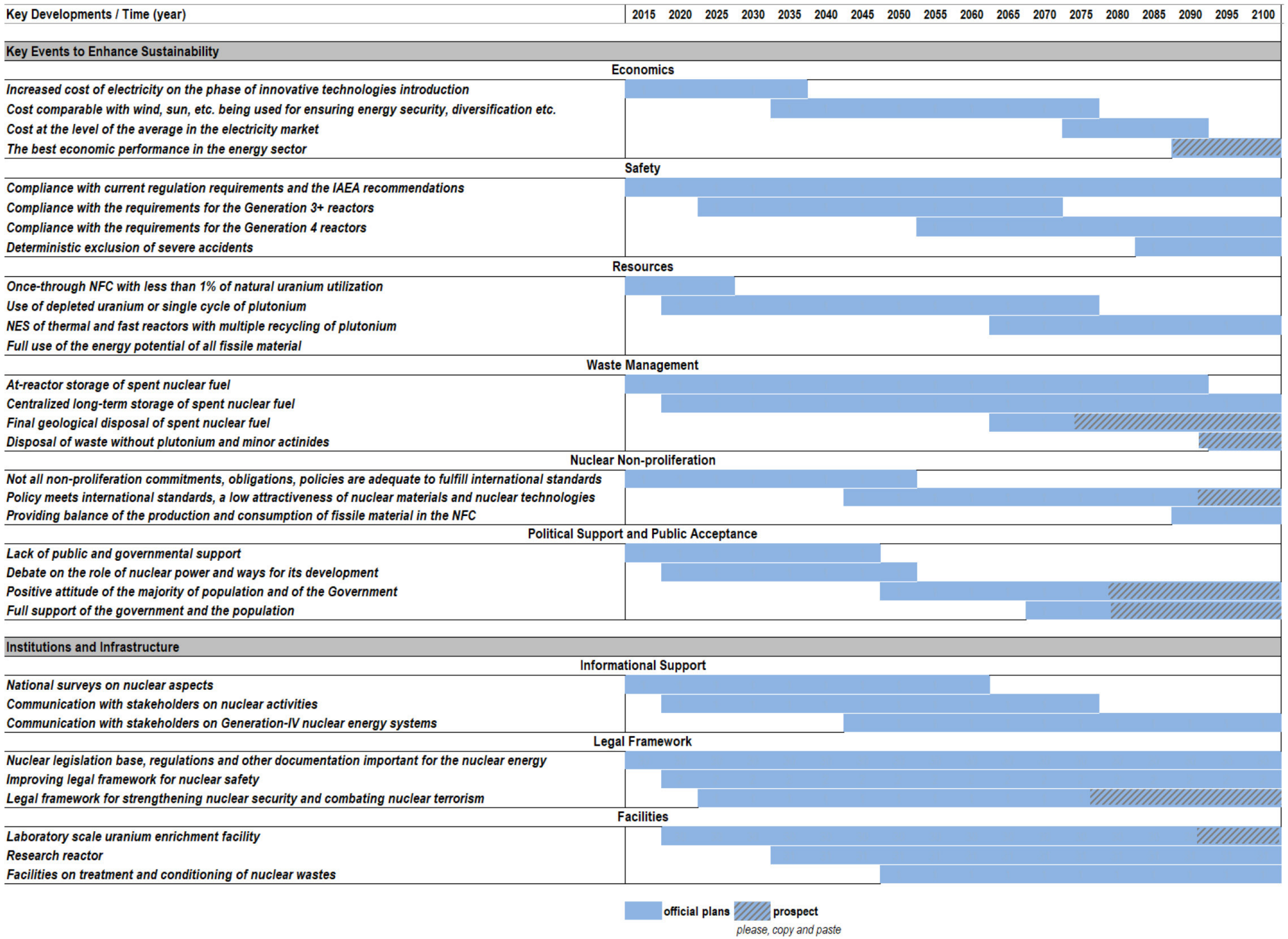


FIG. 23. Example of the presentation of key tasks and developments for a hypothetical case.

tools. Official plans need to be clearly differentiated from the projection (for instance, by using a black colour for official plans and white colour for prospects for Gantt diagrams and by indicating the ‘prospects’ by shading the area on the associated graphs).

A visual demonstration of the required and existing capacities for all stages of the nuclear fuel cycle taking into account development plans and pointing to potential challenges within different timeframes can be provided using either a Gantt chart presentation, stacked columns, or stacked areas plots (Fig. 24).

Gantt charts can provide a detailed presentation of quantitative data on nuclear fuel cycle activities both from the demand and the supply sides, while stacked column and stacked area graphs are better suited to demonstrate trends. In some cases, for example, for a small scale national nuclear energy programme, it is preferable to use stacked column graphs rather than stacked area plots, which are better suited for large scale nuclear energy programmes or for regional or global roadmaps, or to accurately reflect official plans.

Screenshots may be made of individual segments or the whole composition including the associated Gantt chart or stacked column or area plot to be placed in the roadmapping study report.

3.5.1. Reactor fleet

The section ‘Reactor fleet’ provides for input on total reactor installed capacities for selected timeframes (Fig. 25). For a case where each of the reactors is described individually, the associated lines on the graph present the reactor installed capacity from its commissioning to its final shutdown. If the intention is to present the evolution of a group of reactors with a single line, this line would show the increasing or decreasing total capacity of all of them.

3.5.2. Energy production

The data for the section ‘Energy production’ from a given nuclear reactor fleet averaged within the selected timeframes can be specified directly. Time steps may be obtained by using detailed energy planning models directly or can be simply evaluated by multiplying the average installed capacities by the corresponding average load factors that have to be additionally specified in the worksheet. The data on load factors can be specified for each individual reactor unit or for the whole nuclear reactor fleet.

3.5.3. Uranium mining and milling

The section ‘Uranium mining and milling’ is completed with information on nationally available uranium resources and national uranium consumption; it is also completed with data on the uranium supply and demand balance (Fig. 26). If a country has certain export obligations to deliver natural uranium abroad the section titled ‘Provide services / transfer out materials’ makes it possible to reflect such responsibilities. The level of detail in this section is decided by experts, depending on the specific objective of the roadmapping and on the available data.

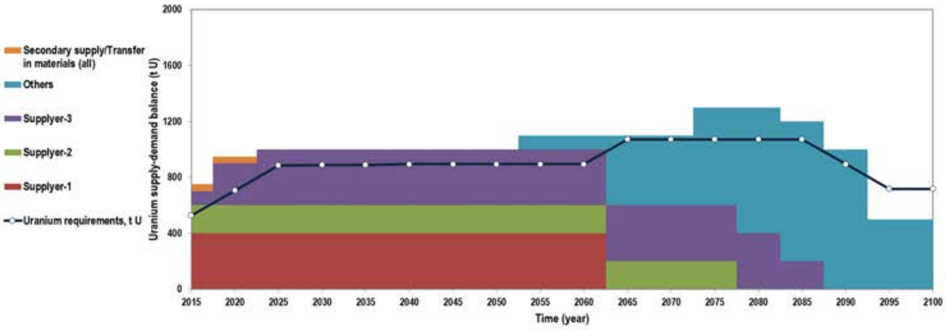
In the ‘supply’ part, all existing primary and secondary supply options for natural uranium production need to be indicated. Primary supply can include the current supply, supply under development, planned supply, projected mines and the secondary supply, which can include commercial inventories, government inventories, re-enrichment of depleted uranium and other sources.

The ‘surplus’ part is completed with data on the balance, from one side, of the existing and required capacities of uranium mining and milling taking into account domestic requirements and export obligations and, from the other side, data on all available primary and secondary supply sources of natural uranium.

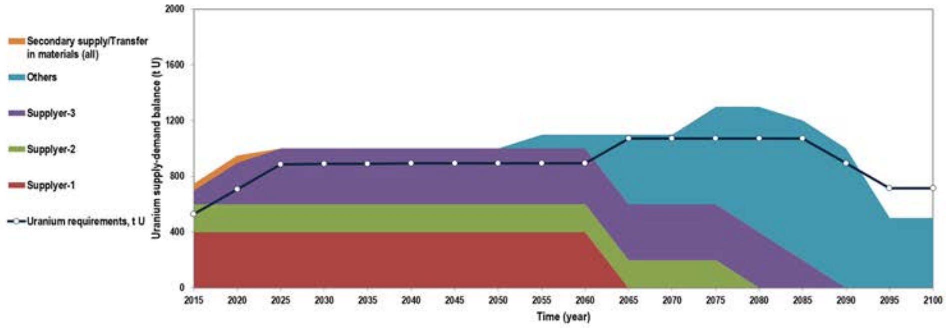
The graphic part provides visualization of the natural uranium demand and of the potential structure of uranium supply. Different options exist to build such a graph. For example, the domestic demand and export commitments can be reflected together or independently. A particular option can be selected by experts depending on the specific objective of the roadmapping performed. The data on natural uranium

Uranium requirements, t U	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Uranium requirements for Unit-1	175	175	175															
Uranium requirements for Unit-2	175	175	175	175	175													
Uranium requirements for Unit-3	179	179	179	179	179	179	179											
Uranium requirements for Unit-4		179	179	179	179	179	179	179	179	179	179	179	179	179				
Uranium requirements for Unit-5			179	179	179	179	179	179	179	179	179	179	179	179	179			
Uranium requirements for Unit-6				179	179	179	179	179	179	179	179	179	179	179	179	179		
Uranium requirements for Unit-7						179	179	179	179	179	179	179	179	179	179	179	179	179
Uranium requirements for Unit-8								179	179	179	179	179	179	179	179	179	179	179
Uranium requirements for Unit-9											179	179	179	179	179	179	179	179
Uranium requirements for Unit-10															179	179	179	179
Total, t U	529	708	886	890	890	894	894	894	894	894	1073	1073	1073	1073	1073	894	715	715
Provide services/Transfer out materials																		
Provide services/Transfer out materials, t U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provide services/Transfer out materials (all)																		
Supply																		
Primary supply/Utilize services, t U	700	900	1000	1000	1000	1000	1000	1000	1100	1100	1100	1100	1300	1300	1200	1000	500	500
Supplyer-1	400	400	400	400	400	400	400	400	400	400								
Supplyer-2	200	200	200	200	200	200	200	200	200	200	200	200	200					
Supplyer-3	100	300	400	400	400	400	400	400	400	400	400	400	400	400	200			
Others									100	100	500	500	700	900	1000	1000	500	500
Secondary supply/Transfer in materials, t U	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Secondary supply/Transfer in materials (all)	50	50																
Total supply, t U	750	950	1000	1000	1000	1000	1000	1000	1100	1100	1100	1100	1300	1300	1200	1000	500	500
Surplus (supply - demand)																		
Surplus, t U	221	242	114	110	110	106	106	106	206	206	27	27	227	227	127	106	-215	-215

(a)



(b)



(c)

FIG. 24. Examples of data presentation. (a) Gantt chart; (b) stacked column graph; (c) stacked area plot.

consumption for a given reactor type utilizing nuclear fuel with a certain enrichment can be directly taken from a reliable reference source or it can be calculated, for example, using the appropriate reactor database.

3.5.4. Conversion

The 'Conversion' section is to specify the domestic demand and possible export commitments (if the country has or is considering entering into obligations to provide conversion services to foreign customers) for uranium conversion services. These need to be specified (in tonnes of uranium) for each reactor or reactor group. The options to meet the conversion demand also need to be specified. Uranium conversion includes two groups of activities: producing UO_2 for reactors that use natural uranium and producing uranium hexafluoride (UF_6) for reactors fuelled with enriched uranium. Which options are to be reflected in the worksheet is decided by experts taking into account the specifics of a national nuclear energy programme.

Total installed capacity, MW(e)	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Unit-1	1000	1000	1000															
Unit-2	1000	1000	1000	1000	1000													
Unit-3	1000	1000	1000	1000	1000	1000	1000											
Unit-4		1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000				
Unit-5			1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000			
Unit-6				1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000		
Unit-7						1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Unit-8								1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Unit-9											1000	1000	1000	1000	1000	1000	1000	1000
Unit-10															1000	1000	1000	1000
Total, MW(e)	3000	4000	5000	5000	5000	5000	5000	5000	5000	5000	6000	6000	6000	6000	6000	5000	4000	4000

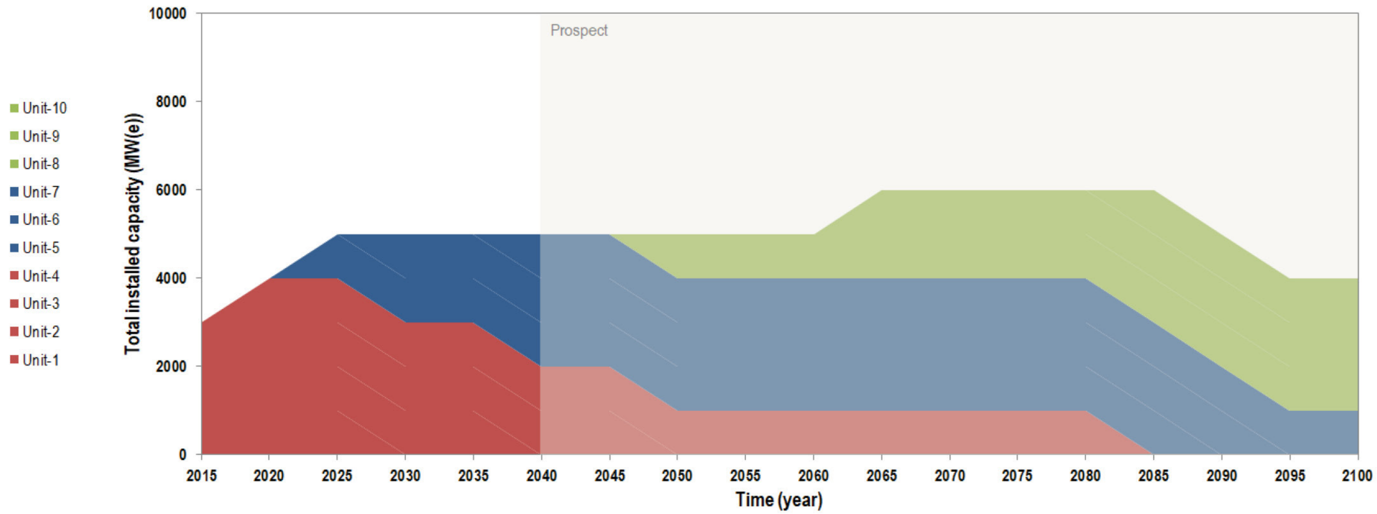


FIG. 25. Example of 'Reactor fleet' presentation (stacked area plots).

Uranium requirements, t U	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Uranium requirements for Unit-1	175	175	175															
Uranium requirements for Unit-2	175	175	175	175	175													
Uranium requirements for Unit-3	179	179	179	179	179	179	179											
Uranium requirements for Unit-4		179	179	179	179	179	179	179	179	179	179	179	179	179				
Uranium requirements for Unit-5			179	179	179	179	179	179	179	179	179	179	179	179	179			
Uranium requirements for Unit-6				179	179	179	179	179	179	179	179	179	179	179	179	179		
Uranium requirements for Unit-7						179	179	179	179	179	179	179	179	179	179	179	179	179
Uranium requirements for Unit-8								179	179	179	179	179	179	179	179	179	179	179
Uranium requirements for Unit-9											179	179	179	179	179	179	179	179
Uranium requirements for Unit-10															179	179	179	179
Total, t U	529	708	886	890	890	894	894	894	894	894	1073	1073	1073	1073	1073	894	715	715
Provide services/Transfer out materials																		
Provide services/Transfer out materials, t U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provide services/Transfer out materials (all)																		
Supply																		
Primary supply/Utilize services, t U	700	900	1000	1000	1000	1000	1000	1000	1100	1100	1100	1100	1300	1300	1200	1000	500	500
Supplyer-1	400	400	400	400	400	400	400	400	400	400								
Supplyer-2	200	200	200	200	200	200	200	200	200	200	200	200	200					
Supplyer-3	100	300	400	400	400	400	400	400	400	400	400	400	400	400	200			
Others									100	100	500	500	700	900	1000	1000	500	500
Secondary supply/Transfer in materials, t U	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Secondary supply/Transfer in materials (all)	50	50																
Total supply, t U	750	950	1000	1000	1000	1000	1000	1000	1100	1100	1100	1100	1300	1300	1200	1000	500	500
Surplus (supply - demand)																		
Surplus, t U	221	242	114	110	110	106	106	106	206	206	27	27	227	227	127	106	-215	-215

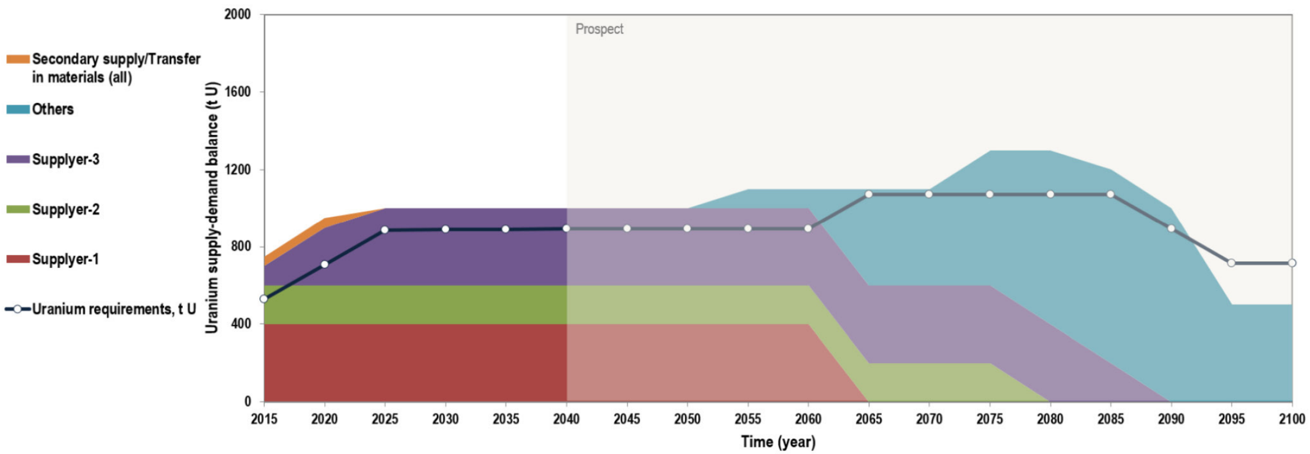


FIG. 26. Example of the 'Uranium mining and milling' presentation (stacked area plots).

Data on uranium conversion services required for the production of nuclear fuel for a reactor of particular type can be obtained from vendors, from reliable information sources or it can be calculated using the reactor database provided with the roadmap template.

The ‘supply’ part includes primary supply options (e.g. domestic facilities, joint ventures, regional centres), secondary supply options (e.g. commercial inventories, government inventories, re-enrichment of depleted uranium) and potential import of conversion services from abroad. Based on the data specified in the ‘demand’ and ‘supply’ parts, the surplus or deficit of the existing and required capacities for uranium conversion can be evaluated. The corresponding data can then be presented graphically to help identify any needs for additional suppliers or options for exporting uranium conversion services for a given reactor fleet within each of the selected timeframes.

3.5.5. Enrichment

The ‘Enrichment’ section enables the characterization of the demand and export obligations of a country regarding uranium enrichment services. The inputs are in tonnes of separative work (SW) (Fig. 27). The data needed to populate this worksheet can be obtained from reliable reference sources or assessed using the reactor database of the roadmap template.

Similar to the ‘Uranium mining and milling’ and the ‘Conversion’ sections, the population of this worksheet requires the specification in the ‘supply’ section regarding primary and secondary supply options and the potential import of enrichment services from abroad. This can help evaluate the deficit or surplus of enrichment services in selected timeframes and visualize existing and planned supply options and export commitments.

3.5.6. Fuel fabrication

The ‘Fuel fabrication’ section allows the input of data on fuel fabrication, including demand for fuel fabrication services and export obligations. The inputs are given in tHM. Available fuel fabrication capacities both domestic and overseas can be considered (Fig. 28).

The main parts of this section are the same as in the ‘Uranium mining and milling’, ‘Conversion’ and ‘Enrichment’ sections. However, unlike the uranium, conversion and enrichment markets, the fuel fabrication market does not provide a fungible high-tech product that may be used as a nuclear fuel for any reactor type. On the contrary, nuclear fuel is a rather individual product adapted for a specific reactor type. Therefore, for an adequate reflection of supply and demand balances, distinctions are to be made between different nuclear fuel types.

In a case when reactors utilize different types of fuel, new lines specifying different fuel types and corresponding total demands can be added. The same procedure is to be applied for the ‘surplus’ section where balances can be calculated based on the supply and demand data for different fuel types.

3.5.7. Spent fuel storage

The section ‘Spent fuel storage’ is intended to elicit the supply–demand balance for spent nuclear fuel storage services in terms of the cumulative flows of spent nuclear fuel to be stored at different domestic storage facilities (at-reactor, away-from-reactor dry and wet storage facilities) or to be forwarded abroad to regional spent nuclear fuel storage facilities for follow-up treatment (Fig. 29). To simplify evaluations, in the demand part it is reasonable to reflect all spent nuclear fuel discharged from reactors. If this is done, the cumulative volume of reprocessed spent nuclear fuel also needs to be taken into account when the supply part is specified. It is also possible to reflect only the spent nuclear fuel that is planned to be stored — in this case, the spent nuclear fuel that has to be reprocessed would be excluded from consideration to avoid double counting. Which option to select is the responsibility of experts, but once the corresponding option is selected this would need to be described in the roadmapping study report.

Enrichment requirements, t SWU	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Enrichment requirements for Unit-1	139	139	139															
Enrichment requirements for Unit-2	139	139	139	139	139													
Enrichment requirements for Unit-3	149	149	149	149	149	149	149											
Enrichment requirements for Unit-4		149	149	149	149	149	149	149	149	149	149	149	149	149				
Enrichment requirements for Unit-5			149	149	149	149	149	149	149	149	149	149	149	149	149			
Enrichment requirements for Unit-6				149	149	149	149	149	149	149	149	149	149	149	149	149		
Enrichment requirements for Unit-7						149	149	149	149	149	149	149	149	149	149	149	149	149
Enrichment requirements for Unit-8								149	149	149	149	149	149	149	149	149	149	149
Enrichment requirements for Unit-9											149	149	149	149	149	149	149	149
Enrichment requirements for Unit-10															149	149	149	149
Total, t SWU	428	577	727	737	737	747	747	747	747	747	896	896	896	896	896	747	598	598
Provide services/Transfer out materials																		
Provide services/Transfer out materials, t	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provide services/Transfer out materials (all)																		
Supply																		
Primary supply/Utilize services, t SWU	600	800	800	800	800	800	1000	1000	1000	1000	1000	1000	1000	800	800	600	400	200
Supplyer-1	600	600	600	600	600	600												
Supplyer-2		200	200	200	200	200	200	200	200	200	200	200	200					
Supplyer-3							800	800	800	800	800	800	800	800	800	600	400	200
Secondary supply/Transfer in materials, t	50	50	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Secondary supply/Transfer in materials (al	50	50	50	50														
Total supply, t SWU	650	850	850	850	800	800	1000	1000	1000	1000	1000	1000	1000	800	800	600	400	200
Surplus (supply - demand)																		
Surplus, t SWU	222	273	123	113	63	53	253	253	253	253	104	104	104	-96	-96	-147	-198	-398

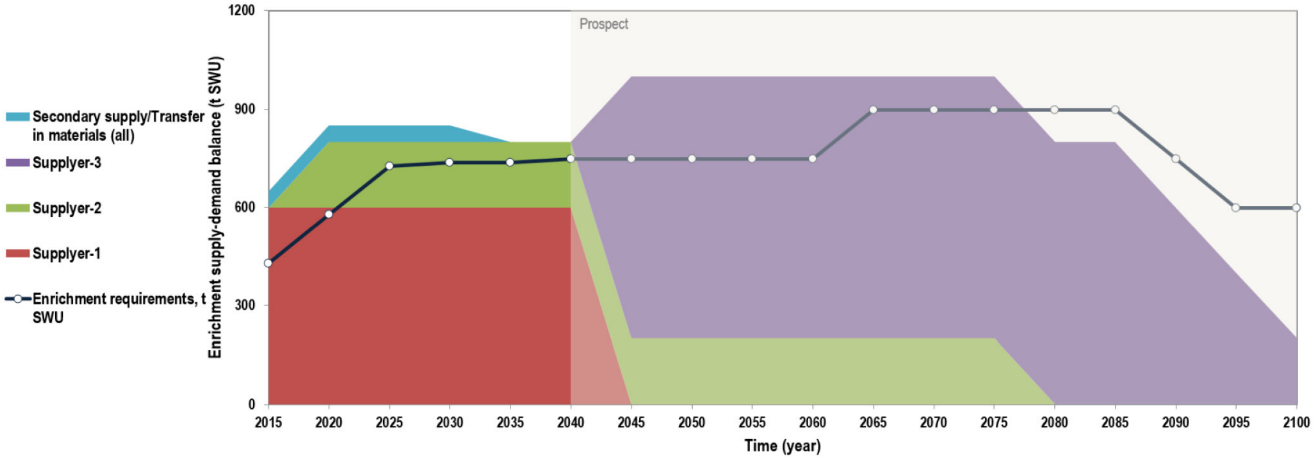


FIG. 27. Example of the 'Enrichment' presentation (stacked area plots).

Fuel fabrication requirements, t HM	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Fuel fabrication requirements for Unit-4		21	21	21	21	21	21	21	21	21	21	21	21	21				
Fuel fabrication requirements for Unit-5			21	21	21	21	21	21	21	21	21	21	21	21	21			
Fuel fabrication requirements for Unit-6				21	21	21	21	21	21	21	21	21	21	21	21	21		
Fuel fabrication requirements for Unit-7						21	21	21	21	21	21	21	21	21	21	21	21	21
Fuel fabrication requirements for Unit-8								21	21	21	21	21	21	21	21	21	21	21
Fuel fabrication requirements for Unit-9											21	21	21	21	21	21	21	21
Fuel fabrication requirements for Unit-10															21	21	21	21
Total, t HM	69	90	111	108	108	105	105	105	105	105	126	126	126	126	126	105	84	84
Provide services/Transfer out materials																		
Provide services/Transfer out materials, t HM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provide services/Transfer out materials (all)																		
Supply																		
Primary supply/Utilize services, t HM	100	150	150	150	150	150	150	150	150	150	150	150	170	120	120	120	120	120
Supplyer-1	100	100	100	100	100	100	100	100	100	100	100	100						
Supplyer-2		50	50	50	50	50	50	50	50	50	50	50	50					
Supplyer-3													120	120	120	120	120	120
Supplyer-4																		
Secondary supply/Transfer in materials, t HM	10	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Secondary supply/Transfer in materials (all)	10	10	10															
Total supply, t HM	110	160	160	150	150	150	150	150	150	150	150	150	170	120	120	120	120	120
Surplus (supply - demand)																		
Surplus, t HM	41	70	49	42	42	45	45	45	45	45	24	24	44	-6	-6	15	36	36

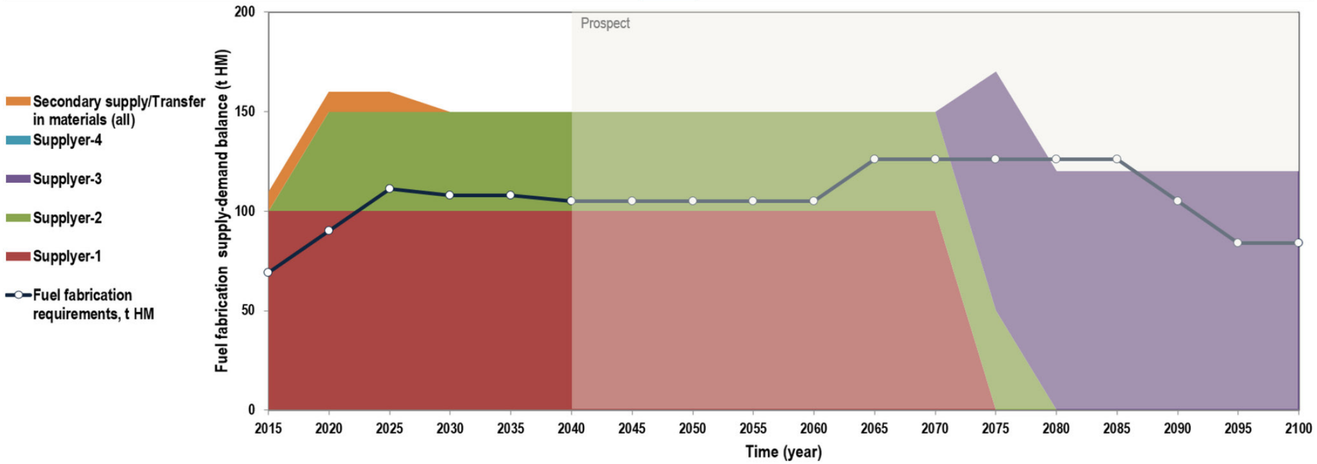


FIG. 28. Example of the 'Fuel fabrication' presentation (stacked area plots).

SNF storage requirements, t HM	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
SNF storage requirements for Unit-1	320	440	560	560	560	560	560	560	560	560	560	560	560	560	560	560	560	560
SNF storage requirements for Unit-2	320	440	560	680	800	800	800	800	800	800	800	800	800	800	800	800	800	800
SNF storage requirements for Unit-3	305	410	515	620	725	830	935	935	935	935	935	935	935	935	935	935	935	935
SNF storage requirements for Unit-4		105	210	315	420	525	630	735	840	945	1050	1155	1260	1365	1365	1365	1365	1365
SNF storage requirements for Unit-5			105	210	315	420	525	630	735	840	945	1050	1155	1260	1365	1365	1365	1365
SNF storage requirements for Unit-6				105	210	315	420	525	630	735	840	945	1050	1155	1260	1365	1365	1365
SNF storage requirements for Unit-7						105	210	315	420	525	630	735	840	945	1050	1155	1260	1365
SNF storage requirements for Unit-8							0	105	210	315	420	525	630	735	840	945	1050	1155
SNF storage requirements for Unit-9							0	0	0	0	105	210	315	420	525	630	735	840
SNF storage requirements for Unit-10							0	0	0	0	0	0	0	0	105	210	315	420
Total, t HM	945	1395	1950	2490	3030	3555	4080	4605	5130	5655	6285	6915	7545	8175	8805	9330	9750	10170
Provide services/Transfer in materials																		
Provide services/Transfer in materials, t HM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provide services/Transfer in materials (all)																		
Supply																		
Primary supply/Utilize services, t HM	1700	1850	2600	2750	3300	3700	4100	4700	4900	5100	5300	5500	5700	5900	6100	6300	6500	6700
At-reactor-pools	1500	1650	1800	1950	2100	2250	2400	2550	2700	2850	3000	3150	3300	3450	3600	3750	3900	4050
Dry away-from-reactor storage	200	200	400	400	800	800	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Wet away-from-reactor storage			400	400	400	600	600	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
SNF reprocessing						50	100	150	200	250	300	350	400	450	500	550	600	650
Geological disposal repository												300	600	900	1200	1500	1800	2100
Transfer out materials, t HM	0	0	0	0	0	0	0	100	200	300	400	500	600	700	800	900	1000	1100
Transfer out materials (all)								100	200	300	400	500	600	700	800	900	1000	1100
Total supply, t HM	1700	1850	2600	2750	3300	3700	4100	4800	5100	5400	5700	6000	6300	6600	6900	7200	7500	7800
Surplus (supply - demand)																		
Surplus, t HM	755	455	650	260	270	145	20	195	-30	-255	-585	-915	-1245	-1575	-1905	-2130	-2250	-2370

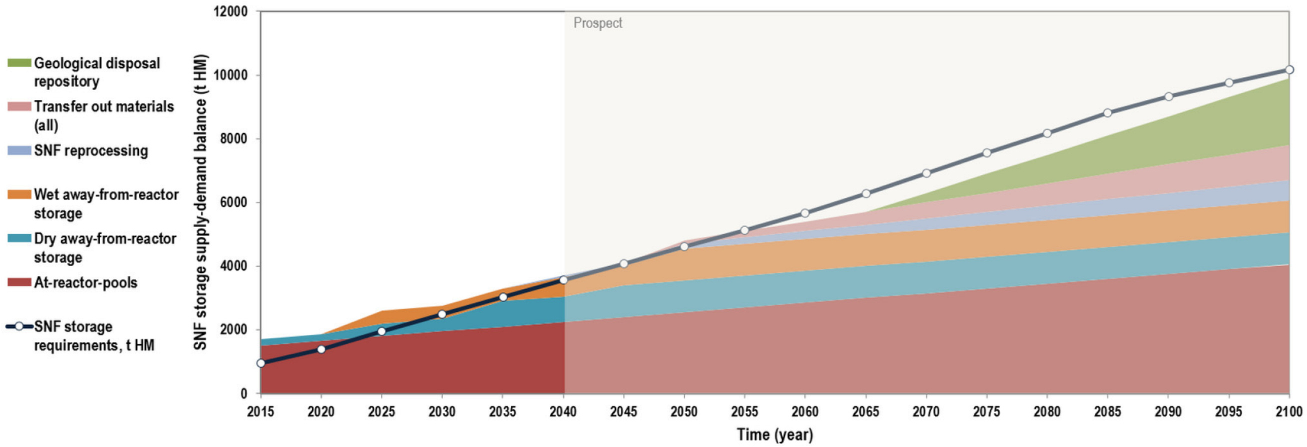


FIG. 29. Example of the 'Spent fuel storage' presentation (stacked area plots).

Another important point is that before proceeding to the first time step the information on the historical spent nuclear fuel amount available by the roadmap starting point needs to be collected or this amount needs to be evaluated. Such collection or evaluation can be done outside of the roadmap template (and its spreadsheet realization, ROADMAPS-ET) and then specified as an input data.

If needed, the user can specify the 'Provide services/Transfer in materials' and 'Transfer out materials' sections. This is to be done when a country has obligations to return foreign spent nuclear fuel or plans to send its spent nuclear fuel abroad for further processing. Based on these data the surplus, that is the differences between the existing and the required capacities for spent nuclear fuel storage, would be calculated and stacked graphs would be drawn reflecting both the existing options for spent nuclear fuel storage and relevant requirements for the domestic and foreign reactor fleets.

3.5.8. Spent fuel reprocessing

The section 'Spent fuel reprocessing' is intended to reveal the supply–demand balance for spent nuclear fuel reprocessing services in terms of flows averaged over certain periods. Populating this section is, in general, similar to filling out the sections related to the nuclear fuel cycle front end. The reprocessing demand for spent nuclear fuel from each reactor type within different timeframes needs to be specified. The 'Provide services/transfer in materials' line allows countries' obligations to reprocess foreign spent nuclear fuel to be taken into account. When needed, it can be subdivided into individual components.

The supply part consists of 'primary supply', the 'primary supply/utilize services' and 'transfer out materials' worksheets that are intended to characterize the domestically available capacities of reprocessing plants and the spent nuclear fuel amount planned to be sent abroad for reprocessing. The degree of detail included here depends on data availability and on the scope of the roadmapping to be performed. The surplus line reflects the balance of the existing and required capacities for spent nuclear fuel reprocessing and, depending on the scope of the roadmapping, the balance can be specified with or without taking into account export and import capabilities.

The graphic part visualizes the supply–demand balance for spent nuclear fuel reprocessing services showing existing and planned capacities for reprocessing from various suppliers. Also shown are requirements for these capacities for domestic and foreign (if any) reactor fleets.

3.5.9. Geological disposal

The section 'Geological disposal' is to intended to elicit the supply–demand balance for geological disposal services. Similar to the 'Spent fuel storage', this section necessitates the input of data on the cumulative flows of spent nuclear fuel or HLW to be disposed (domestic and foreign) and on the corresponding capacities of repositories (both domestic repositories and those potentially available abroad). At the time of writing, final decisions on the selection of a waste management strategy had been postponed in many countries. Therefore, this section may happen to contain no data or the user may face problems in populating it. In such cases this section can be excluded from the roadmapping study report.

The section 'Geological disposal' concludes a series of input data sections on the nuclear fuel cycle front end and back end. Depending on the focus areas of a particular roadmap, additional sections can be introduced when necessary to reflect some other features of the nuclear fuel cycle, such as plutonium production and consumption, thorium utilization, HLW management and transport. This is to be defined by the experts performing a particular roadmapping study.

3.6. INTEGRATION, CROSS-CUTTING ANALYSIS AND CONDENSED PRESENTATION OF ROADMAPS

3.6.1. Collections of roadmaps

As has already been mentioned in Section 2.4.3, both top-down and bottom-up approaches can be applied for the aggregation of roadmaps (Fig. 30). A top-down approach starts with building a combined regional, multiregional or global NES. This NES can be further broken down into its constituent parts — national or regional NESs. In the top-down approach, major assumptions regarding the combined NES are formulated without going into details of the constituent national or regional NES. A bottom-up approach is the piecing together of national or regional NESs to arrive at a combined, aggregated regional or global NES. In the bottom-up approach, national or regional NESs that are constituents of the combined NES can be specified in detail from the outset. They are then combined together until a complete aggregated upper-level NES is developed. The relative benefits of the bottom-up approach and why it has been selected as the basic approach in the ROADMAPS collaborative project are explained in Section 2.4.3.

Within the ROADMAPS collaborative project, the following has been noted regarding roadmap aggregation:

— The metrics in all of the roadmaps under aggregation needs to be kept standard; then it can be summarized in a straightforward way.
— The key developments and nuclear fuel cycle requirements can be used for cross-cutting analyses performed by countries considering collaboration (trade) as an approach to enhance the sustainability of a national NES. Unlike the 'Metrics' section, this section allows a certain freedom in data presentation.

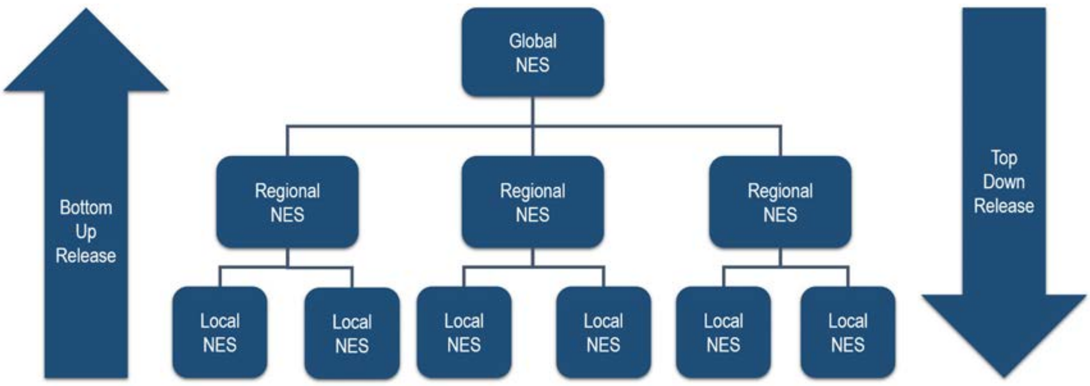


FIG. 30. Bottom-up and top-down approaches to roadmaps aggregation.

3.6.2. Progress monitoring

The roadmap template incorporates provisions for progress monitoring of the NES deployment strategy for enhanced sustainability. In ROADMAPS-ET it is realized in the "Status monitoring" section. The provisions include a set of quantitative indicators specified by experts in line with the specific objectives (targets, milestones) of the roadmapping performed. The indicators can be defined to perform an evaluation in relative terms (Fig. 31). The tracking and monitoring of the NES deployment strategy against roadmap milestones involves:

- Monitoring indicators that characterize the expected enhancement of NES sustainability in different areas owing to technological and institutional innovations and/or increased collaboration with other countries and the key points (or milestones) that, when reached, indicate that certain sustainability enhancements have been achieved;
- The desired (or target) values of monitoring indicators that characterize reaching the key points (milestones).

3.6.3. Condensed roadmap

The roadmap template includes detailed information on national plans and projections for enhancing nuclear energy sustainability, such as long term nuclear power profiles and material flows in the nuclear fuel cycle. Along with the detailed roadmap, it appears reasonable to provide a condensed roadmap version, which would present a concise, illustrative and interactive report in a single figure based on the detailed roadmap (Fig. 32). Such a condensed presentation of a roadmap allows interested stakeholders, and primarily decision makers, to faster and more effectively understand the main aspects of the elaborated detailed action plan. In ROADMAPS-ET, the condensed roadmap can be build in the “Condensed roadmap” section.

Moreover, the limitations on data and information disclosure can be a significant issue, while the detailed roadmap can contain certain information and data that are sensitive or confidential. For this reason, the condensed roadmaps can also be useful for communications with the broader public or targeted new foreign partners, for example.

The condensed roadmap can include several key structural elements combined by common logic to characterize the current state and plans or projections for NES development in the short, medium and long terms.

The ‘timeline’ displays the chronological order of an NES deployment scenario within short, medium and long term periods.

The ‘elements’ are the main components needed for NES sustainability enhancement, chosen by experts from a country to present the official plans and projections for national NES evolution. Basically, the ‘elements’ is an information block, which can describe components such as either the growth and the scale of an NES, the directions of nuclear fuel cycle development or collaboration with other countries and forms of its implementation.

The ‘element item’ is to characterize the evolution (e.g. development or deployment) of an element over particular periods of time, including technical parameters, economic performance and infrastructure and institutional arrangements. A country expert can specify element items for each element or according to his or her preference.

The specification of element items is intended to reflect official plans and non-official projections, including alternative scenarios, of NES evolution towards enhanced sustainability.

A country expert can use additional elements to clarify transition points, decisions made and the correlation of scenarios within different elements (Fig. 22).

When all of these structural elements are combined, it becomes possible to develop a full scale condensed roadmap reflecting all areas rated important by a country. In practical applications, time steps can be changed depending on the key development and task considered. Also, additional elements, element items and scenarios can be added.

Figure 33 provides an example of a condensed roadmap. This example is only for illustration purposes. The presented condensed roadmap includes the elements described in brief below.

Status Monitoring (Quantitative Indicators)	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Uranium/thorium utilization	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Geologic waste production	1.00	0.98	0.97	0.94	0.94	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Enrichment utilization	1.00	1.01	1.02	1.03	1.03	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05

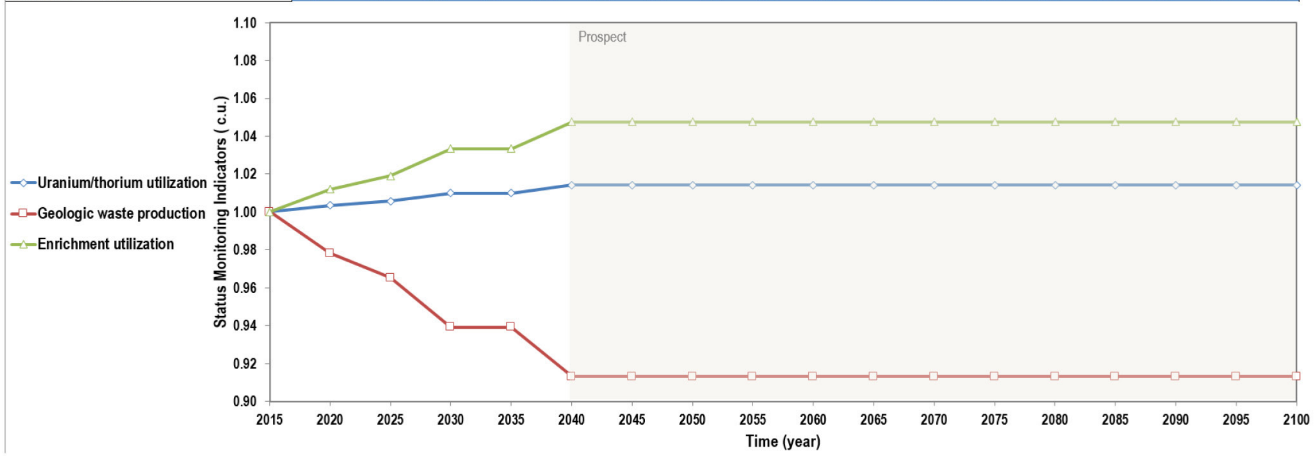


FIG. 31. Example of the 'Status monitoring' presentation .

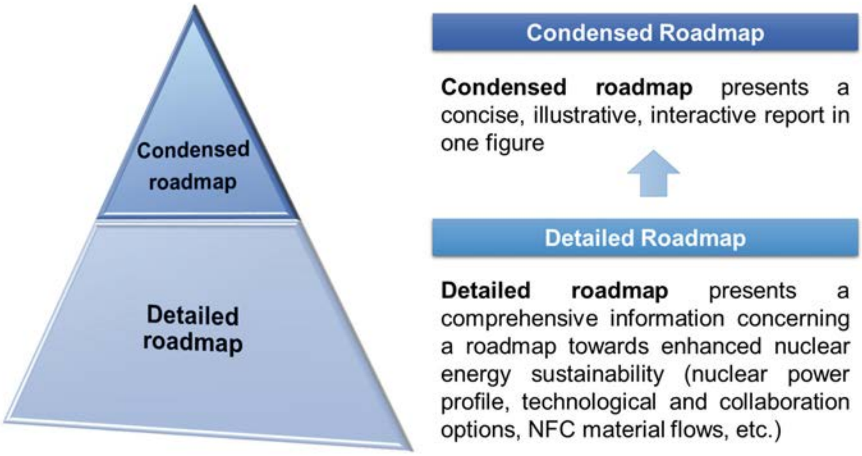


FIG. 32. Roadmap visualization approaches.

3.6.3.1. Nuclear power status

The element ‘nuclear power status’ specifies the currently observed and expected growth of nuclear power capacities and of the total installed capacity of nuclear power. The following scenarios of capacity growth are possible: stabilization, small growth (below 0.1 GW(e)/year) and medium growth (0.1–0.5 GW(e)/year).

The items characterizing the total installed capacities of nuclear power are as follows: low (0–10 GW(e)), medium (10–50 GW(e)) and high (>50 GW(e)). Each of these is considered under three timeframes: the short term (from the current year to 2030), medium term (2030–2050) and long term (2050–2100).

The items characterizing energy products include electricity and, in this example, hydrogen production; combined heat and power applications can also be included.

3.6.3.2. Technology options

The element ‘technology options’ indicated available domestic technology options and technology options abroad to which the country in question has access. Several options can be specified simultaneously. The following items may be included: once-through nuclear fuel cycle, recycle of spent nuclear fuel with only physical processing, limited recycling of spent nuclear fuel, complete recycling of spent nuclear fuel, transmutation or incineration of minor actinides or minor actinides and fission products, and final geological disposal of all wastes.

3.6.3.3. Reactor fleet and nuclear fuel cycle activities

The element ‘reactor fleet and nuclear fuel cycle activities’ specifies the reactor types to be considered in the reactor fleet. It is possible to list individual reactors (for countries with small nuclear programmes) or reactor groups (for countries with a large reactor fleet comprising different reactor types). The evolution of a group of reactors can be accompanied by transition nodes of different lengths, depending on the time period. Different reactor types and associated fuel chains are combined creating a multiplicity of NES arrangements aimed at achieving specific goals, such as a better use of resources and the minimization of radioactive waste.

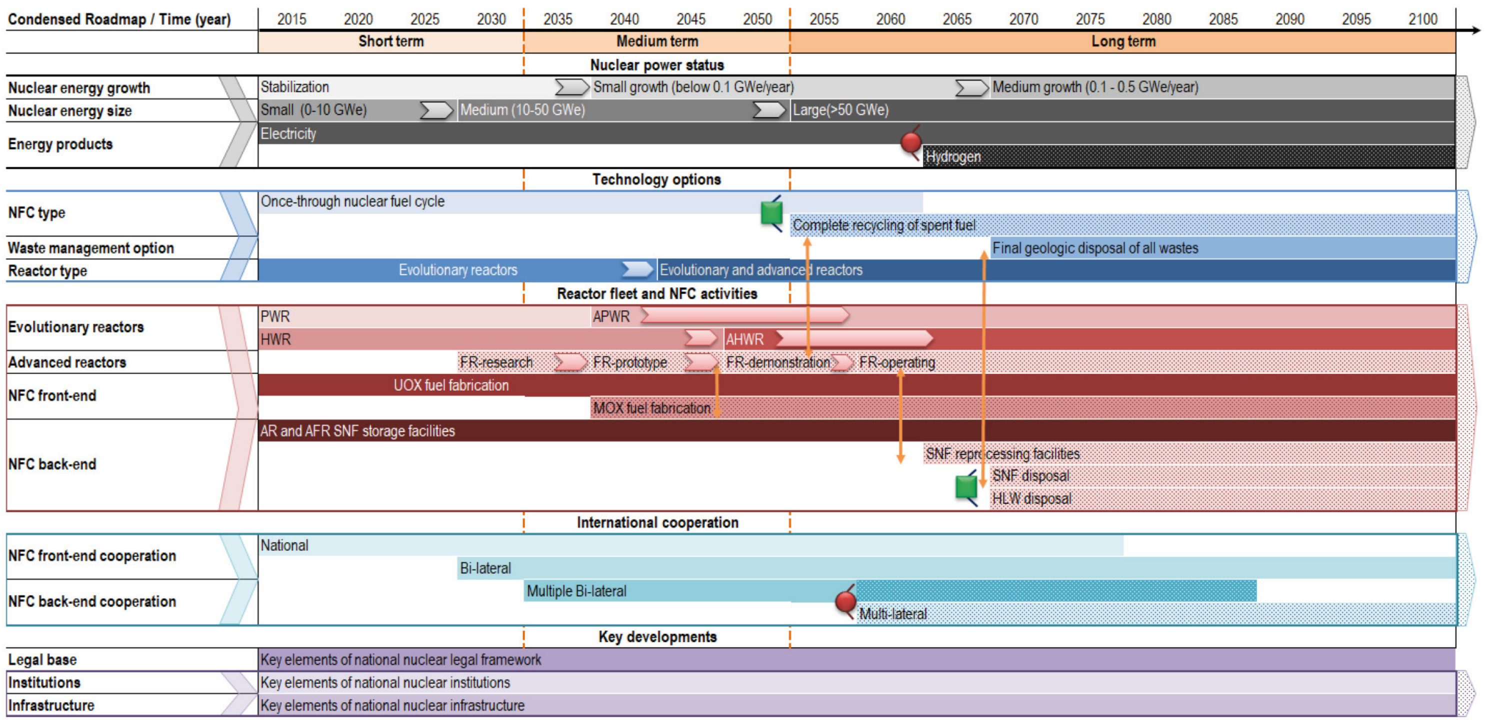


FIG. 33. Example of a condensed roadmap.

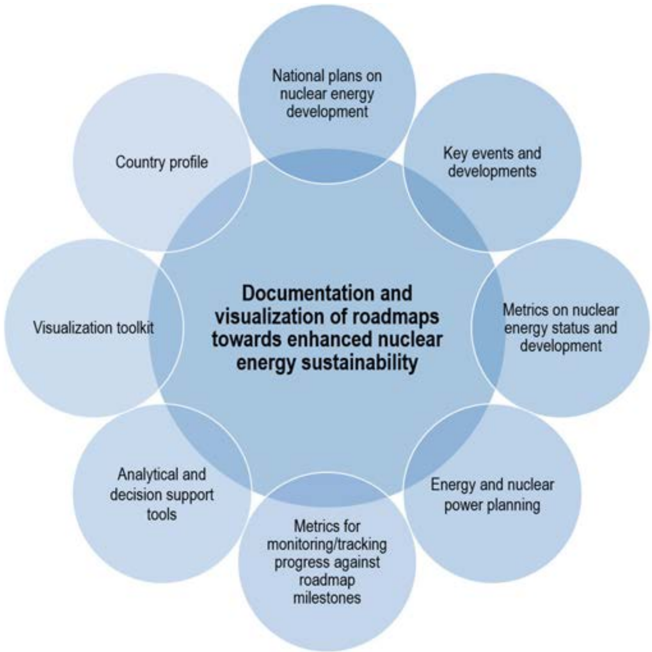


FIG. 34. The data flows needed to document the status and plans for national nuclear power development within the roadmap template.

3.6.3.4. Collaboration with other countries

The element 'collaboration with other countries' specifies the types of collaboration (trade) with other countries in areas where such collaboration takes place or is planned (or projected) within different timeframes. The following possible forms of collaboration (trade) are included: national only, under a bilateral agreement, under multiple bilateral agreements, under a multilateral agreement.

3.6.3.5. Key developments and tasks

The element 'key developments and tasks' is intended to visualize the important aspects of nuclear industry development in a country. The inputs are to be identified by the country's experts. The following element items (to be specified throughout the timeline) are included: legal base, institutions and infrastructure.

3.7. ROADMAPS-ET TOOL TO SUPPORT ROADMAPPING FOR ENHANCED NUCLEAR ENERGY SUSTAINABILITY

Roadmapping for enhanced nuclear energy sustainability requires an extended application of different analytical tools. Among them are different quantitative analytical software and qualitative visualization tools combined with subject matter specialized codes that allow the structuring and effective presentation of the required information and data.

Figure 34 shows the main data flows needed to document the status and credible plans for national nuclear power development. The analytical software tools, databases and sources of information that can be helpful in performing roadmapping for enhanced nuclear energy sustainability are described in brief in Section 2.4.4. Described in this section is the ROADMAPS Excel based tool (ROADMAPS-ET) — a dedicated tool developed within the framework of the ROADMAPS collaborative project to support the overall project objective.

ROADMAPS-ET — an spreadsheet realization of the roadmap template — is an open to modifications by the user flexible and universal tool designed for the analysis and presentation of analytical results regarding NES deployment strategies for enhanced sustainability at a national, regional or global level. ROADMAPS-ET can be used for strategic planning, analytical studies, the preparation of reporting documentation for management and summaries for the media regarding issues related to enhancing NES sustainability.

ROADMAPS-ET provides sufficient flexibility to present a variety of NES options and NES deployment scenarios; it can be helpful in the identification of the merits and disadvantages of a particular NES option or scenario. It can also help identify possible measures to enhance NES sustainability in different timeframes and under different boundary conditions.

The roadmap template and the associated ROADMAPS-ET tool incorporate recent methodological achievements and best practices in the area of the development and presentation of national nuclear energy roadmaps for enhancing nuclear energy sustainability. They provide for:

- Presentation of official plans and longer term projections for NES deployment and relevant infrastructure development;
- Specification of associated technological and collaboration forks;
- Progress monitoring towards enhanced NES sustainability;
- Condensed and detailed presentation of a roadmap for enhanced nuclear energy sustainability;
- Aggregation (integration) of roadmaps and relevant cross-cutting analysis.

Being combined with topical NES scenario modelling and comparative evaluation toolkits, the roadmap template supports:

- A more specific examination of NES deployment plan implementation from both technology and collaboration related standpoints;
- An analysis of the availability and readiness of the industrial and institutional infrastructure for a given NES deployment scenario;
- Performing appraisals of certain collaboration options in each of the nuclear fuel cycle activities.

The ROADMAPS-ET tool, which is a spreadsheet realization of the roadmap template, is not a computational code but an analytical decision support tool for structuring and unifying data on issues related to NES sustainability enhancement using the Gantt charts.

The ROADMAPS-ET tool has been developed on the basis of recommendations from participants and observers of the ROADMAPS collaborative project and from Member States who were participants in the 11th INPRO Dialogue Forum Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems convened in October 2015 at IAEA headquarters. This tool is intended for qualified experts capable of taking into consideration all of the factors associated with the specification of a roadmap for enhanced nuclear energy sustainability. When needed, other specialized software can be used to populate the roadmap template, as highlighted in Section 2.4.4.

The specific features of the ROADMAPS-ET tool are as follows:

- The tool incorporates feedbacks from trial roadmapping studies performed within the ROADMAPS collaborative project and presented in Sections 4 and 5 of this publication.
- Consistency with existing IAEA and other open access nuclear power and nuclear fuel cycle related databases and information sources (The Power Reactor Information System [27], Nuclear Fuel Cycle Information Systems [28], the World Nuclear Association (WNA) [29], WISE-URANIUM [30], etc.).
- An aggregation functionality enabling the construction of regional or global roadmaps based on national and regional roadmaps with a given level of detail.
- A capability to be integrated with external material flow analysis tools and nuclear fuel cycle calculators.

— The tool can be easily modified by the end user.
— Ease of use (no installation is needed; no macros are included — it is simply a spreadsheet file).

The ROADMAPS-ET and instructions for its use are provided as supplementary files in the on-line version of this publication. To support the application guidance provided in the user instructions, supplementary files also offer a hypothetical example of roadmap development.

4. SUMMARY, CONCLUSIONS AND PATH FORWARD

This section summarizes major findings and conclusions of the ROADMAPS collaborative project and outlines possible applications of the roadmap template and ROADMAPS-ET. It also presents an insight on possible follow-up activities to the ROADMAPS collaborative project.

4.1. SUMMARY OF DEVELOPED PRODUCTS AND SERVICES

The following products and services have been developed within the INPRO collaborative project ROADMAPS:

— The roadmap template, representing a structured approach for enhancing globally sustainable nuclear energy sustainability, providing models for cooperation among countries and a framework for documenting actions, scope of work and timeframes for specific collaborative efforts by particular stakeholders;
— An approach for the bottom-up integration of national roadmaps to derive a regional or global projection of a pathway towards enhanced nuclear energy sustainability;
— ROADMAPS-ET supporting the practical application of the above mentioned approaches and the analysis and visualization of the results;
— Examples of a trial application of the roadmap template and the integration approach in a series of case studies performed by project participants;
— Training materials and on-line consultancy services provided by the IAEA on the above mentioned tools.

Interested Member States can use the above mentioned products and services for roadmapping towards the sustainability enhancement of their national NES. These products and services can be used by interested technology user (including newcomer) and technology holder countries to carry out collaborative long term nuclear energy planning towards enhanced sustainability with integration of the developed roadmaps on a global and regional (not necessarily geographical) basis.

4.2. CONCEPT AND SCOPE OF ROADMAPPING

Roadmapping in this publication is understood as developing long term nuclear energy planning towards enhanced nuclear energy sustainability through both technology innovation and cooperation among countries.

Regarding innovations in technology, several options were considered, starting from operating systems that provide contribution to the security of energy supply and meet the current requirements for safety, economics, environmental protection and non-proliferation, and ending up with advanced systems in which all actinides are recycled and only fission products are finally disposed.

Collaboration (trade) among countries was proven important as it can help to amplify the benefits of technology innovation and bring them even to those countries that do not plan to deploy innovative nuclear technologies domestically.

Roadmapping towards enhanced nuclear energy sustainability addresses the timelines, the technologies, the institutional mechanisms and the economic arrangements that support a collaborative enhancement of nuclear energy sustainability, as well as the drivers and impediments for such an enhancement. In this, the roadmap is assumed to indicate, among other things, where savings in time, effort and resources could be achieved through collaboration with other countries.

Roadmapping is assumed to be based on official national plans (when available) in the short to medium term (typically until 2020–2035) and also on longer term projections based on national studies (up to 2100). As such, roadmapping requires periodic updates as plans are corrected and new studies on projections are performed and, therefore, it would benefit from being established as a continuous process rather than a one-time effort.

Carrying out roadmapping for a national NES can assist national strategic planning for nuclear energy development. When roadmapping is performed in cooperation between technology users and possible technology providers, an additional benefit resulting thereof is strategic insights into the international market of products and services for peaceful applications of nuclear energy. Therefore, synergies leading to enhanced sustainability can be achieved regardless of the development of the countries involved in cooperation (e.g. two newcomers can achieve synergies by working together).

4.3. THE ROADMAP TEMPLATE AND ROADMAPS-ET

Experts from 17 Member States have developed the roadmap template — an analytical tool supporting the development of a structured approach to enhancing nuclear energy sustainability, providing models for cooperation among countries and a framework for documenting actions, scope of work and timeframes for specific collaborative efforts by stakeholders. The roadmap template includes the following main components:

— General country information;
— National plans and perspectives on nuclear energy development;
— Metrics on nuclear energy status and development;
— Key developments;
— Condensed roadmap;
— Reactor fleet, energy production and nuclear fuel cycle evolution;
— Integration and cross-cutting analysis;
— Progress monitoring;
— Reactor database and information sources.

This approach is supported by nuclear energy planning and scenario analysis tools.

The ROADMAPS collaborative project has developed a framework for both detailed and condensed roadmaps. The condensed roadmap summarizes major elements of a detailed roadmap to provide a concise, illustrative and interactive report in one figure.

The ROADMAPS project has also developed an approach for bringing out a global perspective on the evolution of nuclear energy based on individual countries' roadmaps developed in a unified and compatible format.

Participants in the ROADMAPS project have developed ROADMAPS-ET to make the applications of the roadmap template more efficient. The tool and the accompanying user instructions are provided with the on-line version of this publication.

4.4. THE BENEFIT OF APPLYING ROADMAPPING AND THE ROADMAP TEMPLATE

Within the ROADMAPS collaborative project, further elaboration and advance of the sustainability concept applied to nuclear energy was provided by consolidating general approaches and tools within a common roadmapping framework. Such a consolidation makes the NES sustainability concept easier to understand for policy and decision makers. Taking into account best practices in roadmapping, the gap oriented approach incorporated within the roadmap template helps to communicate more clearly the challenges regarding the current situation and the prospects of nuclear energy.

The roadmap template suggests a possible format for the presentation of national strategic plans on nuclear energy development and deployment. This unified and standardized format can support the collaboration and integration of different visions on future NESs.

The developed structured approach to enhancing sustainability can potentially be extended for non-electrical applications of nuclear energy or even for a non-nuclear energy system, as essentially the same solutions and principles can be applied to the whole energy mix, and can be used for the preparation of an overall energy master plan.

ROADMAPS-ET was developed to accommodate different situations faced by various countries. In this regard, the following question may arise: What is the difference between a country using the roadmap and without it? Why is it useful to develop a roadmap?

In the domain of nuclear energy, cooperation among countries has proven to be an effective instrument for nuclear energy sustainability enhancement. There are many cooperation options related to technical, economical, human resource and legal aspects, as well as to nuclear trade in a variety of areas, all leading to the enhancement of nuclear energy sustainability. The developed roadmap template provides a wide range of opportunities to enhance NES sustainability through cooperation with other countries for identification and analysis. Especially when roadmapping is performed jointly by two or more countries and the resulting roadmaps are aggregated, this can help highlight the short to medium to longer term balances of supply and demand in products and services related to peaceful applications of nuclear energy. In turn, this will produce an insight into emerging nuclear markets, which can help both suppliers and consumers to better define their long term production and collaboration strategies.

For a newcomer country, roadmapping is important to provide a broader overview to politicians, to tread in the steps of other newcomers in a similar situation, and to investigate the start-up of a nuclear power programme along with its development over time. It should be noted that roadmaps are not developed to convince newcomers to embark on a nuclear energy programme, but to help them in doing so by the provision of some guidelines and examples. The roadmap template can be useful for understanding the nuclear power development process step by step. The examples provided in this publication can be useful for newcomers as they present the best practices of other countries and, in this sense, can serve as a guideline.

4.5. NATIONAL AND AGGREGATED ROADMAPS: INSIGHTS FROM CASE STUDIES

Based on the roadmap template, several national case studies have been performed in a specified format by interested Member States to outline the long term national nuclear energy strategy for moving towards enhanced NES sustainability. At this stage, all studies have been of a trial nature; they were performed to explore the capabilities of the roadmap template and ROADMAPS-ET rather than to develop strategic recommendations to national decision makers.

The trial case studies included general country information, national plans and projections on NES development, metrics on the current state of the NES, key tasks of NES development, reactor fleet, energy production and nuclear fuel cycle installations and services, progress monitoring and other relevant information.

The case studies from Armenia (Annex VIII.2) and Belarus (Annex VIII.3) present the current standpoints of a country with a small electricity grid and a newcomer country, respectively. Both studies consider a once-through nuclear fuel cycle with water cooled thermal reactors as a likely technological option by the end of the century. Armenia and Belarus need to collaborate with other countries on the construction of one or more NPPs and on the sustainability issues of a once-through nuclear fuel cycle. Both countries intend to export their spent nuclear fuel to the vendor or to a nuclear fuel cycle back end service provider.

The case study from Romania (Annex VIII.4) focuses on the needs and security of nuclear fuel supply, on operation performance indicators, and on radioactive waste management, including waste disposal up to 2100. The study has identified the potential for collaboration with other countries in nuclear fuel cycle activities envisaging the benefits for national NES development. The study concluded that obtaining converted uranium under bilateral agreements becomes of interest in the near and medium terms. For the medium and longer terms, obtaining natural or enriched uranium under bilateral or multilateral agreements could be of interest. Obtaining fuel fabrication services and using spent fuel reprocessing services could also be of interest within the longer term timeframe, based on bilateral or multilateral agreements.

The trial case study from Thailand (Annex VIII.5) presents the example of the roadmap template application for a newcomer country. It considers the plan for the long term development of nuclear power for the period up to 2100. The official information and the informed opinions of a group of nuclear professionals were gathered and used as the basic information to fill in metrics on the state of nuclear energy, and to develop the roadmap template in this study. The simplified roadmap visualization for the newcomer country was developed to provide an example of nuclear power planning and scenarios for the country up to 2100.

The trial case study from Ukraine (Annex VIII.6) considered national demands for enrichment, nuclear fuel fabrication and long term spent nuclear fuel storage for the period up to 2100 with the goal of enhancing the sustainability of the national NES. The study identified possible gaps in achieving the sustainable development of the national NES based on a once-through nuclear fuel cycle with long term storage of spent nuclear fuel. Therefore, scenarios explored cooperation with other countries, considering the new national strategy for the development of the energy system of Ukraine until 2035.

The trial case study from the Russian Federation Annex (VIII.7) highlighted the strategy of the Russian Federation which is to expand the synergistic potential of existing and innovative nuclear technologies towards enhanced NES sustainability through mutually beneficial collaboration among countries. The Russian Federation study highlights a high level of involvement in the global markets of services in the nuclear fuel cycle front end. It also highlights prospects for expanding the range of services to the nuclear fuel cycle back end. Reprocessing of foreign spent nuclear fuel, fabrication of new fuel using the fissile and fertile materials extracted from spent nuclear fuel and then employing the refabricated fuel in thermal and FRs is presented as an expanding trend in the domestic practice.

The study on the bottom-up aggregation of the metrics (Annex IX.2) presents an approach to aggregate technology holder, technology user and newcomer countries roadmaps for regional and global analysis. This study is based on a questionnaire performed at the 11th INPRO Dialogue Forum Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems convened in 2015. Participants from 21 Member States have provided their responses to the questionnaire. Particular country's entries were shaped up as a country level simplified (proto) template. Country level metrics were then aggregated into group metrics for technology holders (five countries in total), technology users (seven countries in total) and newcomers (nine countries in total). The study concluded that such an analysis can help harmonize different countries' intentions and resources and facilitate collaboration towards enhanced NES sustainability.

Annex IX.3 presents a trial application of the roadmap template to the scenarios developed in the INPRO GAINS project, including the cross-cutting analysis of roadmap templates for NG1, NG2 and NG3 countries regarding cooperation in nuclear fuel cycle with the indication of key developments, events and relevant metrics. The main purpose of this case study was to apply the roadmap template to the GAINS heterogeneous world model scenario based on the introduction of FRs in the BAU scenario. The study identified savings in time and resources on the way to more sustainable regional and global NESs that could be achieved both through the introduction of innovative nuclear technologies and cooperation among country groups. This analysis also provided a global balance of nuclear materials and services for technology holder and technology user countries.

The study on the roadmap template's application to a global nuclear fuel cycle (Annex IX.4) is an examination of the availability and sufficiency of the global nuclear fuel cycle infrastructure to support the global growth of nuclear power for the evolutionary deployment scenario. The approach considered in this study is based on the evaluation of the supply–demand balances for the most essential nuclear fuel cycle products and services in the medium term. The study has demonstrated that the developed roadmap can be used for diverse purposes, including the analysis of various technological, institutional and structural options that have an impact on NES sustainability enhancement. It has also been shown that the combined use of energy planning tools, open access databases, other information and statistical sources on nuclear power and the nuclear fuel cycle along with ROADMAPS-ET provides a self-sufficient toolkit to develop and present the nuclear energy roadmaps for decision makers, experts and stakeholders.

Annex IX.5 summarizes major observations of the fourth INPRO Dialogue Forum Drivers and Impediments for Regional Cooperation on the Way to Sustainable Nuclear Energy Systems convened in 2012. This forum brought together representatives of the technology holder, technology user and newcomer countries to exchange views on the benefits and issues associated with regional cooperation in building sustainable NESs and, specifically, to understand the standpoints of the newcomer, technology user and supplier countries regarding the driving forces and impediments for such a cooperation.

An overall consideration of the results obtained in the trial case studies indicates that the developed roadmap template is a flexible, multipurpose and easy-to-use analytical tool. It provides specific guidance for developing national roadmaps and examples of how these roadmaps can be used to identify the 'health' level and sustainability of an NES. The roadmap template also helps to indicate weak points and gaps in a country's nuclear energy strategy and to find out where savings in the time, efforts and resources needed to realize the desired option of enhanced NES sustainability could be achieved through collaboration with other countries.

4.6. ENHANCING SUPPORT TOOLS FOR ROADMAPPING

At the time of writing, the roadmap template had been realized as a spreadsheet file. Owing to its architecture and functional capabilities, ROADMAPS-ET can be easily modified by users to consider their preferences regarding the presentation of a variety of options for NES and nuclear energy evolution scenarios.

The experience in the application of the roadmap template and ROADMAPS-ET indicates that further development of the template in uranium recycling and depleted uranium management and a more detailed specification of the closed nuclear fuel cycle could be of benefit. Relevant improvements can also be implemented in ROADMAPS-ET.

Although the use of a spreadsheet was found to be very convenient to introduce parameters and select available options, certain additional improvements have been identified as reasonable. The key direction here is to increase the automatization level of supporting calculations. For example, the population of the 'Metrics' section currently requires substantial user efforts to introduce all the required key information. The aggregation of national roadmaps is another area where automatization would be of benefit.

The path forward and future enhancement of ROADMAPS-ET can also include user interface optimization and web application development. Other software development platforms could also be used for this purpose.

4.7. PATH FORWARD TO REGIONAL AND GLOBAL ROADMAPPING

To develop a broader projection of nuclear market evolution, in the future it might be useful to increase the number of participants involved in roadmapping towards enhanced NES sustainability. It could then be possible to integrate national roadmaps not only on a regional (not necessarily geographical) but also on a multiregional and potentially on a global basis. To facilitate this, the inputs and outputs of the ROADMAPS collaborative project could later be formalized as an updatable electronic tool or database with access limited to roadmapping participants only. An option to integrate roadmaps at any requested level, from bilateral to regional to multiregional would also need to be provided. As multiple national roadmaps are integrated, the combined regional or country level roadmaps might eventually evolve into an integrated plan for enhancing the sustainability of the global NES.

However, the expediency and feasibility of going in the abovementioned direction would need an a priori solid confirmation and strong support from interested Member States. To check on the availability of those, the following steps could be undertaken:

— A dedicated Dialogue Forum could be organized and a brochure summarizing the major outcomes of the ROADMAPS collaborative project for the broad audience could be produced.
— Sections of the roadmap template to be filled out by the forum participants before the Dialogue Forum could be identified, to facilitate follow-up activities on the elaboration of the aggregated roadmap.
— A live on-line video training course on the roadmap template within the INPRO Analysis Support for Enhanced Nuclear Energy Sustainability service for interested Member States could be prepared and delivered.
— A process or software for the aggregation of the inputs from the Dialogue Forum participants could be developed.
— The Dialogue Forum could be convened to include the participants‘ presentations; submitted templates could be aggregated and the results of aggregation discussed with all participants of the forum, to clarify their standpoints regarding going forward along the suggested path to regional and global roadmapping.

REFERENCES

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

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

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual, IAEA-TECDOC-1575 Rev. 1, IAEA, Vienna (2008).

[4] WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT, Our Common Future, Oxford University Press, Oxford (1987).

[5] UNITED NATIONS, United Nations Conference on Sustainable Development, Rio de Janeiro, Brazil, 20–22 June 2012, Agenda Item 10, Outcome of the Conference, A/CONF.216/L.1, UN, New York (2012).

[6] UNITED NATIONS, Transforming our World: The 2030 Agenda for Sustainable Development, A/RES/70/1, UN (2015).

[7] UNITED NATIONS, Sustainable development goals, 17 Goals to transform our world (2015), http://www.un.org/sustainabledevelopment

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, 60th IAEA General Conference (2016), https://www.iaea.org/about/policy/gc/gc60/scientific forum

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power and Sustainable Development, IAEA, Vienna (2016).

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Infrastructure, IAEA Nuclear Energy Series No. NG-T-3.12, IAEA, Vienna (2014).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Economics, IAEA Nuclear Energy Series No. NG-T-4.4, IAEA, Vienna (2014).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Environmental Impact from Depletion of Resources, IAEA Nuclear Energy Series No. NG-T-3.13, IAEA, Vienna (2015).

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Environmental Impact of Stressors, IAEA Nuclear Energy Series No. NG-T-3.15, IAEA, Vienna (2016).

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons Learned from Nuclear Energy System Assessments (NESA) Using the INPRO Methodology, A Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA-TECDOC-1636, IAEA, Vienna (2009).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment of Nuclear Energy Systems based on a Closed Nuclear Fuel Cycle with Fast Reactors, IAEA-TECDOC-1639 (Rev. 1), IAEA, Vienna (2012).

[16] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Assessment of the Planned Nuclear Energy System of Belarus, IAEA-TECDOC-1716, IAEA, Vienna (2013).

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

[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Enhancing Benefits of Nuclear Energy Technology Innovation through Cooperation among Countries: Final Report of the INPRO Collaborative Project SYNERGIES, IAEA Nuclear Energy Series No. NF-T-4.9, IAEA, Vienna (2018).

[19] INTERNATIONAL ATOMIC ENERGY AGENCY, Modelling Nuclear Energy Systems with MESSAGE: A Users' Guide, IAEA Nuclear Energy Series No. NG-T-5.2, IAEA, Vienna (2016).

[20] INTERNATIONAL ATOMIC ENERGY AGENCY, Experience in Modelling Nuclear Energy Systems with MESSAGE: Country Case Studies, IAEA-TECDOC-1837, IAEA, Vienna (2018).

[21] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Multi criteria Decision Analysis Methods to Comparative Evaluation of Nuclear Energy System Options: Final Report of the INPRO Collaborative Project KIND, IAEA Nuclear Energy Series No. NG-T-3.20, IAEA, Vienna (2019).

[22] INTERNATIONAL ATOMIC ENERGY AGENCY, Milestones in the Development of a National Infrastructure for Nuclear Power, IAEA Nuclear Energy Series No. NG-G-3.1 (Rev. 1), IAEA, Vienna (2015).

[23] INTERNATIONAL ATOMIC ENERGY AGENCY, INIR: Integrated Nuclear Insfrastructure Review Missions,

Guidance on Preparing and Conducting INIR Missions (Rev.1), IAEA non serial publication 978 92 0 114610 6, Vienna (2011),
https://www.iaea.org/publications/8654/inir integrated nuclear infrastructure review missions
[24] UNIVERSITY OF CAMBRIDGE, Roadmapping (2021), https://engage.ifm.eng.cam.ac.uk/ifm roadmapping/
[25] PHAAL, R., "Roadmapping for strategy and innovation", Centre for Technology Management Institute for Manufacturing, University of Cambridge, (2015),
http://www.ifm.eng.cam.ac.uk/uploads/Research/CTM/Roadmapping/roadmapping_overview.pdf
[26] SUSTAINABLE NUCLEAR ENERGY TECHNOLOGY PLATFORM, European Sustainable Nuclear Industrial Initiative (2020),
http://www.snetp.eu/esnii/
[27] INTERNATIONAL ATOMIC ENERGY AGENCY, PRIS The Power Reactor Information System (2020), https://pris.iaea.org/
[28] INTERNATIONAL ATOMIC ENERGY AGENCY, Integrated Nuclear Fuel Cycle Information System (iNFCIS), https://www.iaea.org/resources/databases/integrated nuclear fuel cycle information system infcis
[29] WORLD NUCLEAR ASSOCIATION, Nuclear Fuel Cycle,
https://www.world nuclear.org/information library/nuclear fuel cycle.aspx
[30] WORLD INFORMATION SERVICE ON ENERGY, Uranium Project, http://www.wise uranium.org/

INTRODUCTION TO THE SUPPLEMENTARY FILES

The on-line supplementary files for this publication, which can be found on the publication's individual web page at www.iaea.org/publications, contain the ROADMAPS spreadsheet, user instructions, additional information on roadmapping, case studies, additional tools, and examples of regional and global analyses. The IAEA is not responsible for the content of the Member State reports, and all questions must be directed to the individual authors or organizations.

ABBREVIATIONS

BAU	business-as-usual
FR	fast reactor
GCR	gas cooled reactor
GDP	gross domestic product
HLW	high level waste
LFR	lead cooled fast reactor
LWR	light water reactor
NES	nuclear energy system
NG	nuclear strategy
NPP	nuclear power plant
SDG	sustainable development goal
t	tonnes
toe	tonnes of oil equivalent
WWER	water–water energy reactor

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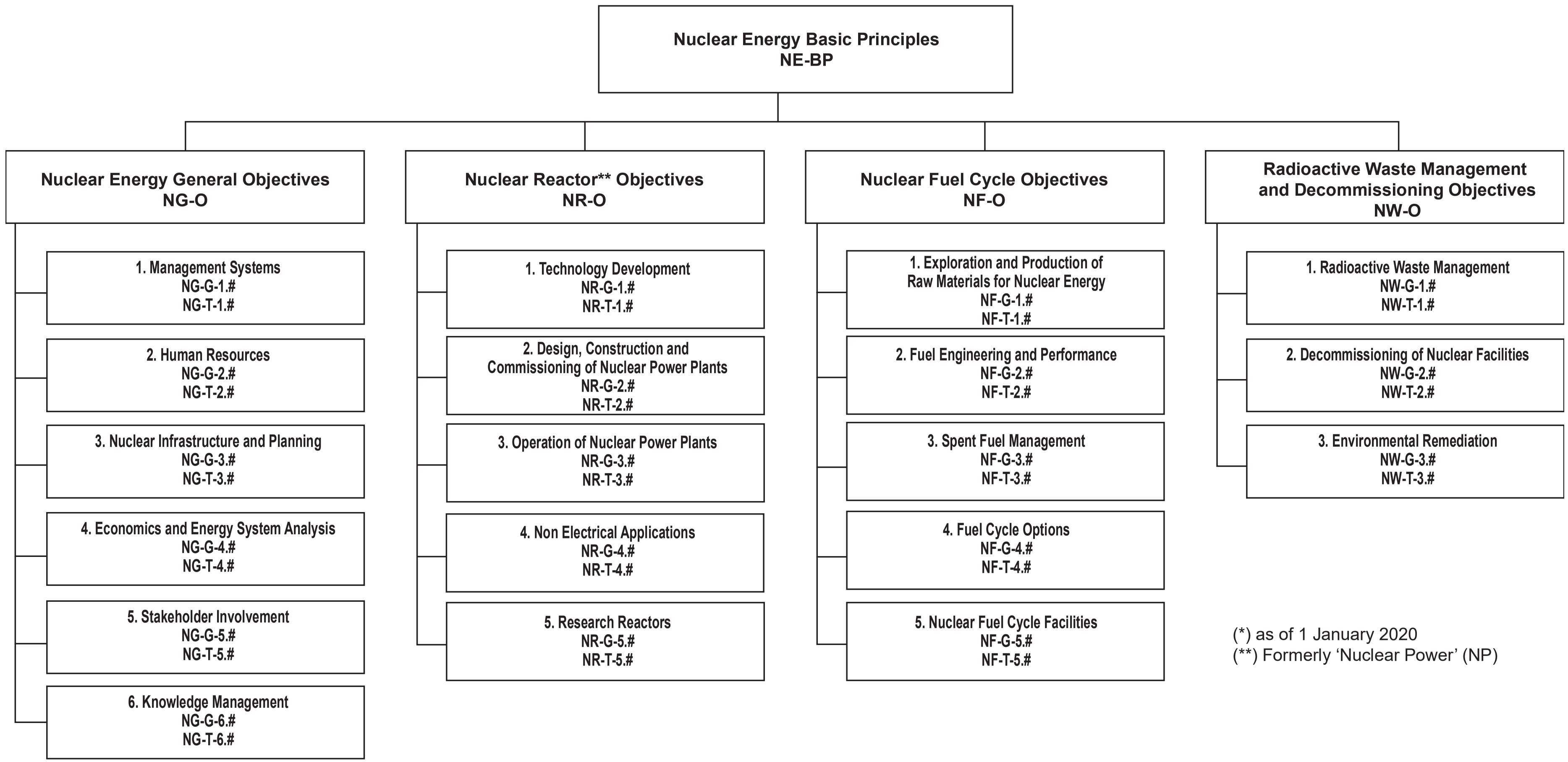

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