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PLANNING ENHANCED NUCLEAR ENERGY SUSTAINABILITY

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IAEA NUCLEAR ENERGY SERIES No. NG-T-3.19

PLANNING ENHANCED NUCLEAR ENERGY SUSTAINABILITY

AN INPRO SERVICE TO MEMBER STATES

ANALYSIS SUPPORT FOR ENHANCED NUCLEAR ENERGY SUSTAINABILITY (ASENES)

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2021

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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.

This publication describes the purpose and scope of the INPRO service Analysis Support for Enhanced Nuclear Energy Sustainability (ASENES). It also highlights the links between this service and overall technical support to Member States for the planning and development of nuclear energy, and explains how it integrates with other IAEA services supporting knowledgeable decision making on nuclear power.

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

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1. INTRODUCTION

1.1. BACKGROUND

Energy is a key input for most human activities. It represents an engine for socioeconomic development and is vital for the provision of basic public services such as health care, education, clean water and sanitation. A lack of access to a reliable, affordable and modern energy supply is a major challenge to achieving the Sustainable Development Goals[1] (SDGs) [1].

As the demand for energy is growing, and expected to continue growing, concerns about energy resource availability, climate change, air quality and energy supply security necessitate careful planning for the development of energy systems, taking into account the long term implications of all energy options and objectively factoring in their technical, economic and environmental considerations. The energy planning process should start by taking stock of a country's overall development stage, using a set of indicators that encompasses all aspects of sustainable development and setting national sustainable development goals and targets. The energy needs for achieving these goals and targets should be assessed. How best these energy needs can be provided for in a sustainable manner, by exploiting available energy resources and employing suitable energy technologies, should be addressed. Since there could be several alternatives, a systematic framework is needed to thoroughly evaluate all future energy supply options and identify potential roles for various energy technologies, including fossil, renewable and nuclear energy, in meeting future energy demand under certain policy or external constraints.

The IAEA has a long history of supporting its Member States in such endeavours. The first project on this topic was launched in the early 1970s to assess the potential role of nuclear power in developing countries [2]. One of the project's main outputs was the development of a systematic methodology for undertaking a comprehensive assessment. Since then, the methodology has been considerably improved and several analytical tools have been developed. In 2009, the IAEA published a brochure entitled IAEA Tools and Methodologies for Energy System Planning and Nuclear Energy System Assessments [3], which introduced an elaborate programme for supporting its Member States in conducting national energy studies and identifying a potential role for various energy technologies, including nuclear power, in meeting their future energy needs. A set of energy planning tools has been developed that facilitates a comprehensive evaluation of energy supply–demand options, taking into account the technical, economic and environmental factors in determining national energy strategies and policies that help achieve national goals and targets for sustainable development. These energy planning tools have been transferred to over 135 Member States and training and guidance on their use in national energy studies has been provided [3].

Once nuclear energy has been identified as a desirable component of a country's future energy mix, it is necessary to perform a detailed evaluation of the entire nuclear energy system (NES) to raise awareness of all the issues associated with the development and deployment of nuclear energy, before making any national decision (Fig. 1).

The IAEA offers technical support to its Member States for all aspects of their nuclear energy programmes. The support is guided by its Medium Term Strategy, which was prepared through a joint consultation process between Member States and the Secretariat to set the direction of the IAEA's programme. One of the strategy's objectives is "facilitating access to nuclear power and other nuclear technologies" through the provision of support to Member States for capacity building, infrastructure development, the dissemination of knowledge and technical information, and the advancement of nuclear technologies [4].

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[1] The heads of states and governments from all around the world met at the United Nations in September 2015 and decided to adopt 17 SDGs aimed at transforming the world over the 15 year period 2016–2030. The 17 SDGs include all areas of critical importance for humanity and the planet, ranging from eradication of poverty, food security, provision of health, education, water and sanitation and affordable and clean energy to protecting the environment, biosphere, and climate and addressing gender gaps and social justice.

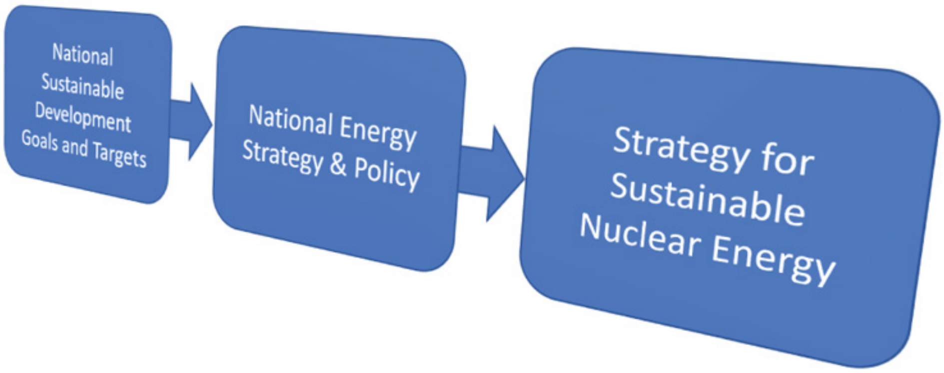

FIG. 1. Developing nuclear energy strategies.

The IAEA's assistance provides technical information, guidance, peer reviews and direct support for strengthening local expertise and skills, as well as for establishing national nuclear institutions to ensure the safe, secure and economic use of nuclear energy. Several programmes and services have been established not only for supporting the technical aspects of nuclear energy development but also for planning and managing it.

One such programme is the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). INPRO was established in 2000 to help ensure that nuclear energy remains available to contribute to meeting global energy needs during the twenty-first century and beyond. It supports Member States in their long term planning for the development of sustainable NESs. Its main activities, known as tasks, focus on four themes: (i) global scenarios; (ii) innovations; (iii) sustainability assessment and strategies; and (iv) dialogue and outreach.

Within INPRO, several collaborative projects have been implemented to support nuclear energy evolution scenario modelling and analysis, the comparative evaluation of NES options and road mapping towards enhanced nuclear energy sustainability. The valuable experience accumulated in these activities can be shared with Member States by providing them with education and training on the application of the methods and relevant software tools developed therein. The development of a proper service can help Member States to build additional capacity to support sustainable nuclear energy development. To achieve this, a new INPRO activity was endorsed by the INPRO Steering Committee in 2017 and started in 2018 with documentation and pilot activities. To facilitate the assessment of the sustainability of innovative NESs, a detailed methodology, the INPRO Methodology for Nuclear Energy System Assessment (NESA), has been developed [5]. NESA is based on INPRO's basic principles and on a set of user requirements, criteria and indicators with acceptance limits, and covers the following areas of assessment: economics, safety (of nuclear reactors and fuel cycle facilities), environment (stressors and resources), waste management, proliferation resistance and infrastructure. INPRO has been offering the NESA service to interested Member States to provide guidance and technical support including data, evaluation tools, guidance documents and so on through a variety of services and activities for conducting national studies to assess the long term sustainability of their nuclear energy programmes. Several countries have applied the INPRO methodology and conducted NESA studies for their planned or ongoing nuclear energy programmes [6, 7].

Under Task 1 — Global Scenarios, INPRO has been performing a scenario analysis of NES evolution to understand major issues for the sustainability of NESs. Several collaborative projects, with the active participation of Member States, have been implemented, from which the main challenges to the development of sustainable NESs emerged. Another project entitled Global Architecture of Innovative Nuclear Energy Systems based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS) focused on the NES at the global level, while the Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES) project went down to national and regional levels.

Global and national studies conducted under these projects highlighted the possibility for win–win cooperation in the nuclear fuel cycle. For most countries with a small nuclear energy programme and newcomer countries it would be uneconomic and technically extremely challenging to establish, at the national level, an NES with a complete fuel cycle, that is, a fully sustainable NES. Cooperation and collaboration among countries, from sharing information to providing products and services (via nuclear trade) to joint ownership of innovative technologies as well as nuclear fuel cycle facilities, would be necessary for achieving the sustainability of nuclear energy at the national, regional and global levels.

A valuable output of these projects was a methodological framework for developing alternative scenarios, reflecting variations in collaboration mechanism among country groups and introduction of innovative technologies, for the evaluation of the sustainability of the resulting NES. Furthermore, the evaluation tools developed under the collaborative projects Key Indicators for Innovative Nuclear Energy Systems (KIND) and Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems (known as ROADMAPS) enabled the quantitative comparison of NES alternatives and scenarios and offered decision support to evaluate alternatives for national development of an NES, also envisioning technically feasible roadmaps. The scenario analysis and decision support frameworks and the evaluation tools have proven to be extremely useful for weighing possible national choices for the scope and extent of national nuclear energy programmes and the needed collaboration with other countries to enhance the sustainability of an NES.

Recognizing the usefulness of INPRO's scenario analysis and relevant decision support tools for national level applications, several Member States recommended that INPRO initiate a new service for providing technical support on NES scenario modelling, analysis and decision support tools to evaluate alternatives for national strategies regarding the development of a more sustainable NES. This recommendation was endorsed by the INPRO steering committee, which is the highest body with representation of all INPRO members that guides its programme.

1.2. OBJECTIVE

Responding to the above mentioned recommendation, INPRO has launched a service to assist and guide Member States in scenario development and analysis as well as to provide decision support for strategic planning that envisages the sustainable development of NESs. The assistance includes: (a) the training of professionals from interested Member States on modelling and scenario analysis of an NES and relevant decision support; and (b) the provision of technical support and guidance for conducting national and regional long term nuclear energy analysis and strategic planning studies, taking into account the potential of technical innovations and cooperation among countries.

The main objective of this publication is to describe the purpose and scope of the INPRO service Analysis Support for Enhanced Nuclear Energy Sustainability (ASENES) and its potential benefits to Member States. The publication also highlights the linkage of this service to the overall technical support offered to Member States for the planning and development of nuclear energy, and how it integrates with other IAEA services supporting knowledgeable decision making on nuclear power.

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

1.3. SCOPE

This publication is intended for planners and researchers in Member States with nuclear energy programmes as well as in those States interested in introducing nuclear energy. It presents the details of a new service launched by INPRO to support national strategic planning and decision making on the development of NESs with enhanced sustainability. It also describes the need for long term strategic planning in order to ensure that the sustainability of an NES is progressively maintained and enhanced, and to demonstrate the usefulness of scenario modelling, analysis and decision support in the comprehensive evaluation of alternatives. The publication also provides an overview of the analytical tools provided by INPRO for scenario modelling and analysis, an evaluation and comparison of NES alternatives and scenarios, and road mapping of NES development towards national, regional and global sustainability. It should be noted that this publication provides only a short overview of the approaches and tools relevant for the ASENES service. Further details can be found in Refs [8–11], which are also mentioned in relevant parts of the publication.

1.4. STRUCTURE

Section 2 presents the concept of sustainability in the context of nuclear energy and describes the need for looking into a much longer term time horizon to secure the sustainability of NESs and cover the intergenerational consequences, both positive and negative, of using nuclear energy. It then elaborates the role of scenario analysis and decision support in the development of and rationale for long term strategies.

Section 3 briefly describes the INPRO frameworks for NES scenario analysis and modelling, the evaluation and comparison of NES alternatives and scenarios, and road mapping towards enhanced NES sustainability.

Section 4 describes the analytical tools developed within various INPRO collaborative projects that are suitable for NES scenario analysis and decision support covering scenario analysis and modelling, the evaluation and comparison of different nuclear technologies and technologies under alternative strategies, assessing the sustainability of NESs and road mapping towards enhanced NES sustainability.

Section 5 describes the new service package offered by INPRO to Member States, elaborating the purpose, scope and various other elements of this service package. It also identifies prospective users of the service and its potential benefits. The section concludes with some remarks on the overall significance and usefulness of the service package.

The Annex presents the guidelines and procedures for requesting and providing the service together with a request form for the service.

2. STRATEGIC PLANNING

2.1. SUSTAINABILITY OF NUCLEAR ENERGY SYSTEMS

INPRO uses a holistic approach in defining an NES. According to it, an NES comprises both facilities and institutions [5]. The facilities make up the entire energy generation and supply chain. At the front end, the facilities are for: (a) mining and milling uranium (or thorium) ore; (b) conversion; (c) enrichment; and (d) fuel fabrication (including the fabrication of mixed oxide (MOX) fuel). After the production of electricity and other energy products from a nuclear reactor, the back end requires facilities for: (a) spent fuel and nuclear waste management, including interim storage; (b) reprocessing of spent fuel, if opted for; and (c) final disposal of nuclear wastes. Throughout the entire supply chain, comprehensive arrangements have to be made to ensure safety and security and to safeguard all the nuclear materials and technologies. For this purpose, national institutions are required to discharge the responsibilities for the legal and regulatory roles, ensure safety and security, and provide technical and scientific support with a high level of competence.

Several technological options are available, while a number of new technologies are being developed for each of the steps of the nuclear energy supply chain. These technologies offer different performance levels for their respective functions and have different costs. Some are more efficient in their intended function while others are more cost effective. Some have reached a maturity level, being already commercialized, while others are still being developed. An appropriate combination of these technologies for the above mentioned steps would determine the overall performance of an NES and its sustainability.

An NES can be characterized as a sustainable system if it meets certain requirements, such as sufficiency and security of the supply of natural resources, economic effectiveness, least burden of wastes, effective proliferation resistance, appropriateness of safety and security, and adequate infrastructure, including the effective functioning of institutions for legal responsibility, the regulatory role, and technical and scientific support. Several INPRO publications [12–16] elaborate the indicators and requirements of a sustainable NES and present guidance for NES sustainability assessment. Following the most frequently used definition of sustainable development first used by the United Nations' World Commission on Environment and Development — that it is "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [17], INPRO has spelled out a three part requirement for an NES to be sustainable:

> "(1) current development should be fit for the purpose of meeting current needs with minimized environmental impacts and acceptable economics; (2) current RD&D programmes should establish and maintain trends that lead to technological and institutional developments that serve as a platform for future generations to meet their needs; and (3) the approach to meeting current needs should not compromise the ability of future generations to meet their needs" [13].

A sustainable NES will directly contribute to achieving SDG 7 — Affordable and Clean Energy, SDG 12 — Responsible Consumption and Production, SDG 13 — Climate Action and SDG 17 — Partnerships to achieve the Goals [1]. A sustainable NES will, therefore, deliver net benefits to society and is expected to have a greater degree of acceptance than an unsustainable one.

Since there could be several technological options for deploying an NES, it is naturally desirable to determine which set of technological options would deliver more sound sustainability. INPRO provides evaluation frameworks and analytical tools for comparing the alternatives for an NES, evaluating and enhancing NES sustainability [8]. The INPRO collaborative projects [9, 10] also identify areas for innovation and improvement, both technological and institutional, and possible mechanisms of international collaboration for enhancing the sustainability of NESs.

At the country level, an NES may contain only a few of the above mentioned steps in the supply chain while the remaining steps are performed elsewhere. This is a common situation found in several countries presently using nuclear power and would be a prudent choice for newcomer countries. INPRO categorizes such countries as 'technology users'. They build, with the support of a supplier country, a nuclear power plant (NPP), import nuclear fuel and store locally the spent fuel and radioactive wastes. They may gradually develop additional facilities of the nuclear supply chain as their national nuclear energy programmes progress, if such options have benefits for the country. For technology users, the sustainability of their local nuclear energy subsystem cannot be assessed separately. The same applies to technology holders, that is the countries that develop NPPs. When countries cooperate or are involved in nuclear trade, sustainability makes sense only in application to an overall NES composed of all cooperating parties. In fact, the sustainability of nuclear energy has to be ensured at a much larger scale — at a regional or even global level — because the various aspects of nuclear energy cut across national boundaries, and the evaluation of the main elements of a sustainable NES (nuclear safety and security, proliferation resistance, minimal production of radioactive waste, availability of natural resources and economic competitiveness) requires consideration of the entire system, including the institutional framework. As such, INPRO approaches for evaluating sustainability [9, 10] encompass a larger landscape and cover all aspects of the NES at the national, regional and global levels.

Nonetheless, in designing a strategy for progressively developing a national NES, in addition to following recommendations [18], a country would need answers to several questions such as: (a) which facilities will ideally be built locally and which services will ideally be outsourced; (b) when would it be cost-effective to build the facilities; (c) what technological options are available, and which would be available in the future, for each of the facility types; and (d) which combination of technology would be more sustainable.

Furthermore, the long term nature of implications for each decision related to the development of an NES necessitates a dynamic consideration of the sustainability concept. The development of a national NES should be considered as a journey with the aim of taking steps in the right direction, which is the direction that would enhance the sustainability of the system with each milestone reached. As more and more technological options become available along the path, the sustainability of the system can be further enhanced. The evaluation of sustainability and the options for its enhancement are, therefore, a continuous process rather than a one-time exercise and it requires the application of tools for the dynamic simulation and analysis of NES deployment.

2.2. NEED FOR LONG TERM NUCLEAR ENERGY PLANNING

Based on energy planning studies, if a Member State determines that nuclear energy is needed as a component of its sustainable energy system, the next step would be to explore long term strategy options for the development of its national nuclear energy programme.

The time frame or horizon to be considered in the case of a nuclear energy programme is different from that for other energy sources. An NPP is a long term commitment that includes infrastructure development, the construction period, the operation period and the decommissioning period as well as final disposal. Spent fuel and radioactive wastes have to be safely stored and safeguarded for a long period of time and eventually disposed of. These activities may span well over 100 years. Moreover, if nuclear energy has been selected as a significant part of the future energy mix, a country is likely to build several NPPs over time.

As such, in order to design a national strategy for the development of a nuclear energy programme comprising several NPP units and fuel cycle facilities built progressively over time, long term serious consideration and evaluation are necessary.

Nonetheless, as a longer time horizon is considered, the inherent uncertainties about the future are confronted. First, it is likely that not only will innovative technologies become available within the nuclear sector but also that there will be technical improvements in other energy sources, challenging the competitiveness of nuclear energy. Second, any quantitative estimates about the technical, economic and environmental performance of nuclear and non-nuclear energy technologies are highly uncertain.

In such a situation, any methodological approach that aims to predict the future is bound to fail. The best recourse is therefore the scenario approach, which explores the future with ‘if–then’ questions to link assumptions and consequences. Scenarios can help in envisioning the future, identifying alternative paths and assessing consequences based on current knowledge. Long term nuclear energy planning should be a process rather than a one-time effort.

Effective realization of the ‘what if’ approach requires the application of tools for the analysis and comparative evaluation of energy system and NES options and scenarios and would benefit from the application of road mapping, that is a structured approach for maintaining and enhancing the sustainability of nuclear energy, providing models for international cooperation and a template for documenting actions, scope of work, and time frames for specific collaborative efforts by particular stakeholders. An NES defined holistically can be effectively analysed by the application of tools enabling the assessment of economic characteristics of a complete NES, not only of its separate components, and therefore also of the dynamic NES evolution scenarios under consideration.

2.3. ROLE OF SCENARIO AND DECISION ANALYSES IN DEVELOPING STRATEGIES

A scenario is a hypothetical sequence of events that involves creating a mental image of a certain situation. The situation may have emerged from events in the past or may arise from events or actions in the future. A scenario describes the possible outcome of a sequence of events, based on assumptions about them and their interplay and consequences. A systematic approach to scenario analysis was developed for military planning to understand the possible outcomes of alternative strategies [19]. During the 1960s and 1970s, the advent of computers enabled the analysis of complex systems with the help of scenario analysis. Scenarios are now widely used for planning in almost all disciplines to explore future possibilities, identify necessary actions and understand their outcomes. In the case of energy, and of nuclear energy in particular, scenario analysis dates back to the 1970s. The pioneering work conducted at the International Institute for Applied Systems Analysis (IIASA), for instance the work by Häfele and Manne on Strategies for a Transition from Fossil to Nuclear Fuels [20], set an example of scenario analysis for exploring long term future energy paths based on the detailed evaluation of technological options and natural resources.

In recent years, scenario analysis has been extensively used for climate change studies under the auspices of the Intergovernmental Panel on Climate Change [21], which defines its scenarios as "images of the future, or alternative futures. They are neither predictions nor forecasts. Rather, each scenario is one alternative image of how the future might unfold".

Scenario analysis can be very valuable in evaluating alternative strategies for the development of nuclear energy. It can provide a systematic framework for combining a large number of factors that may drive future development. Some of the driving forces could be under the control of national decision makers to some extent while the majority of the factors influencing future development would depend upon international and regional conditions.

Decision analysis supplements scenario analysis. For a sound comparison of alternatives, some criterion or a set of criteria has to be clearly defined. It is not enough to declare that alternative 'A' is better than alternative 'B'. Some aspect should be identified, measured and then compared. For example, the efficiency of a system, a piece of equipment or a process can be used to determine the better performance between alternatives. Similarly, the cost of an appliance is a clear aspect that can be used to compare different options. One or more aspects can be chosen to measure the performance of each option and to rank them for making the final choice. This process of defining criteria and metrics, measuring performance, and comparing and ranking alternatives is called the decision support process.

2.4. CONSIDERATIONS FOR DEVELOPING SCENARIOS AND DECISION SUPPORT MODELS

Scenarios are images of the future, created from a set of assumptions and the characteristics of a system. A scenario can be qualitative or quantitative. Qualitative scenarios are based on narratives that describe the future qualitatively. Quantitative scenarios, on the other hand, are based on quantified information about the different states of a system. Scenarios could also be exploratory or of a normative nature. Exploratory scenarios attempt to explore what might happen under different sets of assumptions, given rules about a system dynamic. They sketch an ordered set of possible events, irrespective of their desirability or undesirability. Normative scenarios, conversely, are target or goal oriented, and try to determine what actions should be taken to achieve an endpoint. They take into account the values and interests reflected in setting targets or goals. Not any set of assumptions about the main elements or drivers of a system can be called a scenario; the assumptions have to be logical and rational. The same is true for decision support models.

Scenarios and decision support models should fulfil the following requirements:

— Consistency. The set of assumptions should be internally consistent. There should be a strong internal logic. Any assumptions made about the interaction and correlation of driving forces should have a logical explanation based on technical grounds or past experiences.
— Plausibility. Images of the future should be constructed on the basis of technically feasible system evolution. The assumptions about the main elements should be possible, and the narrative should be credible.

— Transparency. All assumptions should be clearly stated. Any assumptions about the representation of complex subsystems, boundary conditions and interactions within the system and with the surroundings should be transparent.

As there could be several factors or driving forces that determine the evolution of a system, the number of possible combinations representing plausible ranges of variation in these factors would be enormous. A realistic selection procedure would be needed to keep the combinations and therefore the meaningful scenarios considered to a reasonable number.

First, the technical feasibility and plausibility of the assumptions for each of the factors or driving forces should be verified. If an assumption about some factor or driving force is technically impractical, it cannot be part of a useful scenario. For instance, assuming the world population will grow at a rate of 5% annually in the future is not a feasible assumption as the current growth rate is about 1% per year.

Second, the combination of factors or driving forces should be logical and consistent. It would be illogical to assume that in a low economic growth scenario, the overall efficiency of energy use could be higher. This is because a higher efficiency of energy use can only be achieved with the large penetration of new capital stock, that is more new appliances and equipment, which is only likely in a high economic growth case.

Another important aspect to be considered in developing scenarios and decision support models is to select from the various factors or driving forces the critical ones that would have a high impact on the system's performance or evolution and create large uncertainties. Some of the driving forces and their impacts could be well known while others could be very uncertain. Based on the available information and understanding of the system, the critical factors that would have a large impact but are most uncertain can be selected. Those factors or driving forces that would have a low impact are not of much interest for investigation. Likewise, those for which the certainty is high can be treated as constant. Figure 2, adapted from Ref. [22], illustrates a situation with six factors or driving forces for a system. Only two of them are of high importance as their impact is large but highly uncertain. Investigating the outcome of their variation with uncertainties and sensitivity analyses of the system's evolution would be useful to deepen understanding about the system's behaviour.

Since every system interacts with its surroundings, scenarios and decision support models should be developed by taking into account the evolution of surrounding systems. The NES is a part of the overall energy system of a country. The potential role of nuclear energy has to be evaluated by considering all the options for delivering required energy services to society and the economy in a safe, clean and affordable manner. A national decision on nuclear energy should, therefore, be evaluated in the context of a bigger picture for the development of a country, one that is firmly tied to the international environment, as shown in Fig. 3. Therefore, an energy system planning study first needs to be carried out to define the role and/or contribution of nuclear power in meeting the projected energy needs of a country. The IAEA provides assistance to Member States in capacity building in the area of national and regional energy system analysis and planning.

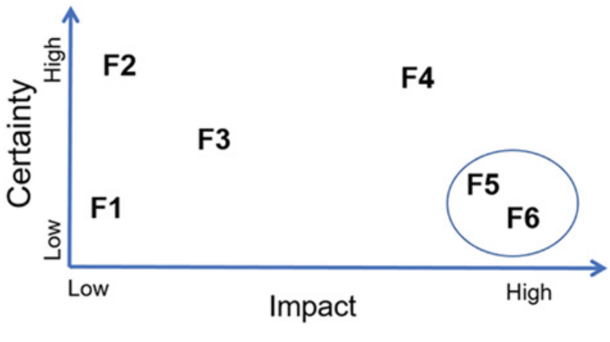

FIG. 2. Selection of factors and driving forces as main scenario elements [22].

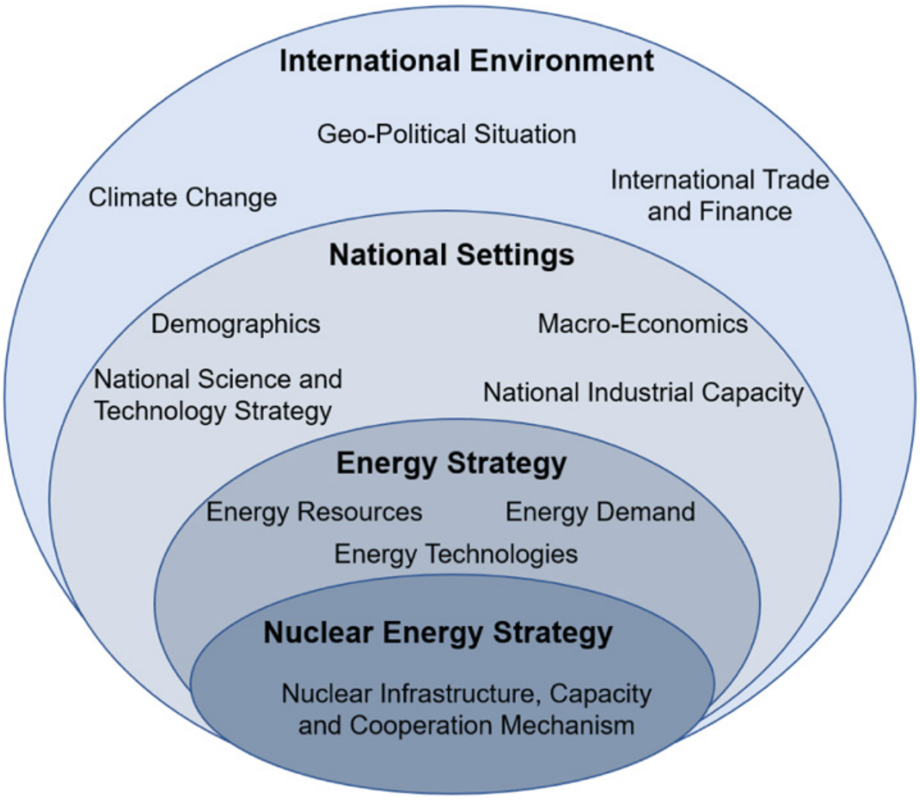

FIG. 3. Linkage of an NES with its surroundings.

3. SCENARIO ANALYSIS AND DECISION SUPPORT FRAMEWORKS

The planning and development of an NES require the consideration of long term responsibilities, implications and consequences. Comprehending the challenges and evaluating possible solutions are vital for designing nuclear energy programmes. Scenario and decision analyses, along with relevant analytical and software tools, can be very helpful in this context. The uncertainties surrounding nuclear technology development and transfer can be incorporated into scenario analysis and decision support, and the performance and evolution of an NES can be evaluated in a systematic manner under an alternative set of assumptions. The INPRO collaborative projects have extensively used scenario analysis and decision support frameworks together with relevant analytical and software tools and have demonstrated their value for exploring the development paths for an NES with enhanced sustainability. The following sections describe the approaches developed under the INPRO umbrella.

3.1. FRAMEWORK FOR NUCLEAR ENERGY SCENARIO ANALYSIS

One of the major INPRO collaborative projects, GAINS, was implemented between 2008 and 2011 [9]. This project was launched as a response to a strong interest expressed by several Member States in developing an understanding of future trends in nuclear energy development at the global level and the potential role of technical innovations and multilateral cooperation for the deployment of a sustainable NES. It was recognized that national strategies in various countries on the development and deployment of different types of nuclear reactors and corresponding fuel cycle facilities may be suboptimum from a sustainability viewpoint when put together in a global landscape. Though the thermal nuclear reactors and their respective fuel cycle technologies in use in the existing fleet would remain the main provider of nuclear energy for several decades, some international studies have concluded that the long term sustainability of nuclear energy cannot be achieved without turning to innovative technologies, including fast reactors and their fuel cycle technologies [23]. However, there are many uncertainties about future trends in nuclear energy development. For example, it cannot be predicted with certainty when innovative reactors and their fuel will become a major part of the future NES. The questions remain of which combination of new reactor technologies and their corresponding fuel cycle will ensure the enhanced sustainability of the NESs and how this transition can be achieved.

These are the main questions the GAINS project aimed to explore through scenario analysis and modelling of the global NES. In the course of the project, a standard methodological framework was developed that facilitates the creation of alternative scenarios for NES evolution with a coherent representation of: (a) the basic components, assumptions and boundary conditions of an NES; and (b) full technical details of various reactor technologies and their corresponding fuel cycles. The framework includes well tested and validated models and tools for material flow simulations and economic evaluations. It also includes an agreed set of metrics for scenario analyses and evaluations.

The GAINS project developed a global model based on three groups of countries decided according to their fuel cycle strategies. Nuclear group (NG1) comprises countries that pursue a general strategy of recycling spent fuel. It is assumed that they will build spent fuel reprocessing facilities and permanent geological disposal facilities for highly radioactive waste. Group NG2 includes countries that follow a strategy either of directly disposing of spent fuel or of sending it abroad for reprocessing. It is assumed that these countries will build permanent geological disposal facilities for either the direct disposal of spent fuel or for reprocessing waste sent from another country. Group NG3 consists of countries that have a general strategy of acquiring fresh nuclear fuel from abroad and sending spent fuel abroad for either recycling or disposal.

Using this country grouping, a global model was developed representing a range of nuclear reactor and fuel cycle technologies, from currently operating reactor systems, to systems planned for near to medium term deployment, to the most innovative systems that are presently at early stages of research and development (R&D). The model was used to develop and analyse several scenarios to understand the possibilities for transition towards a global architecture of innovative NESs.

The GAINS scenarios are based on a heterogeneous world with the above mentioned three country grouping. In one variation, the country groups are assumed to develop their NESs without any cooperation with the other group or groups. Conversely, another variation assumes active cooperation, though to different extents, among the country groupings, including the transfer of technologies and sharing of facilities. These two situations cover the full range of uncertainty regarding cooperation among countries. In the real world, the actual situation will lie somewhere between the two extremes of non-cooperation and full cooperation. The heterogeneous world scenarios are compared with a homogeneous world model[2] (see Fig. 4) [9].

Another factor of high uncertainty in the main elements of GAINS scenarios is the timing of the availability and deployment of innovative technologies. It has been assumed that the advanced light water reactors (LWRs) and heavy water reactors (HWRs) and their respective fuel cycles will be the main technologies for new builds in the near term future, while high temperature reactor technologies are predicted to enter the market around 2030. The recycling of spent fuel in the form of MOX fuel would remain on a limited scale. However, with the introduction of fast reactors around the mid-twenty-first

[2] The homogeneous world model involves full cooperation among different parts of the world and uniform technology implementation (synergistic world). The heterogeneous world model involves either no cooperation (the non-synergistic case) or different degrees of cooperation among the country groups implementing different reactor technologies and fuel cycle strategies (the synergistic case).

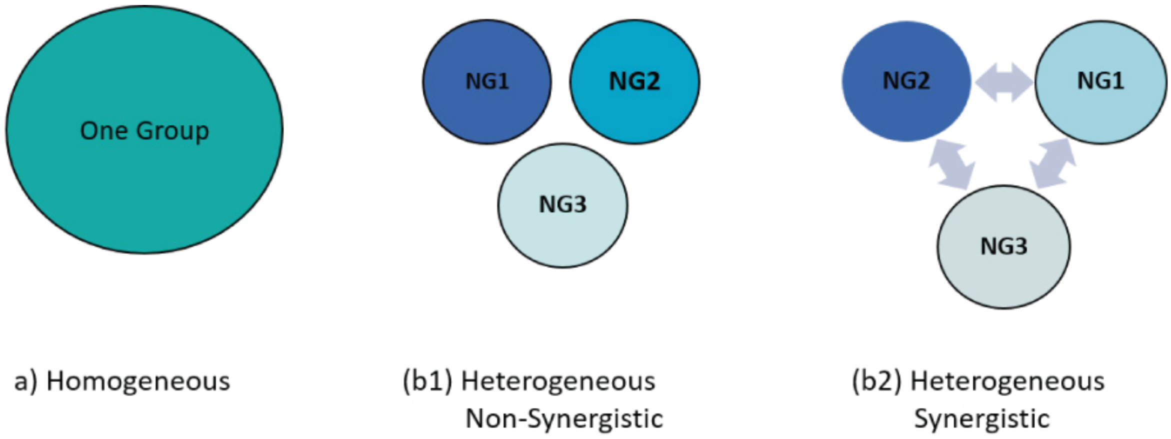

FIG. 4. The country grouping used in GAINS scenarios [9].

century, the reprocessing of spent fuel would become a standard practice in some of the countries developing that technology.

Using these assumptions and technical and economic data for the existing and innovative technologies compiled by the INPRO team, a number of GAINS scenarios were developed to investigate the long term consequences of alternative development paths of global NES. The IAEA's analytical tools Model for Energy Supply System Alternatives and their General Environmental Impacts (MESSAGE) and the Nuclear Fuel Cycle Simulation System were used to obtain quantified results of the alternative scenarios. Additionally, some other tools developed by Member States, such as COSI (France), TEPS (India), FAMILY (Japan), DESAE (Russian Federation) and DANESS (United States of America) were also used for calculations[3] [24–27].

The GAINS scenarios can be compared using the concept of key indicators developed for the INPRO methodology. The GAINS study developed a set of selected key indicators that captured the main focus areas of the GAINS project and allowed the establishment of specific targets to be reached in each focus area — for example, minimum depletion of natural resources, minimum production of radioactive wastes, minimum amount of critical material in storage, and so on. For illustration, Fig. 5 compares the cumulative amount of spent fuel stored in two scenarios: (a) in an NES comprising thermal reactors only; and (b) in an NES with a combination of thermal and fast reactors. This comparison shows how innovative technologies can help in dealing with spent fuel.

This process of: (a) identifying the main elements of scenarios; (b) compiling technical and economic data; (c) developing scenario assumptions; (d) selecting appropriate analytical tools; (e) conducting simulations; and (f) analysing and comparing results is embedded in the GAINS framework [9]. This framework helps measure the extent of transition from an existing NES to a sustainable NES that could be achieved under various scenarios. It can also help identify the possibilities of cooperation among various countries and assess how such cooperation can influence the introduction of innovative technologies and deliver benefits in terms of sustainability of the global NES.

3.2. OPTIONS FOR ENHANCING NUCLEAR ENERGY SUSTAINABILITY

The GAINS project revealed the significance of international collaboration among Member States for enhancing NES sustainability. Several INPRO members expressed strong interest in the further development of the GAINS framework to explore more deeply the synergistic approach as a means to

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[3] COSI: Scenarios Simulation Code; DANESS: Dynamic Analysis of Nuclear Energy System Strategies; DESAE: Dynamic of Energy System Atomic Energy; TEPS: Tool for Energy Planning Studies.

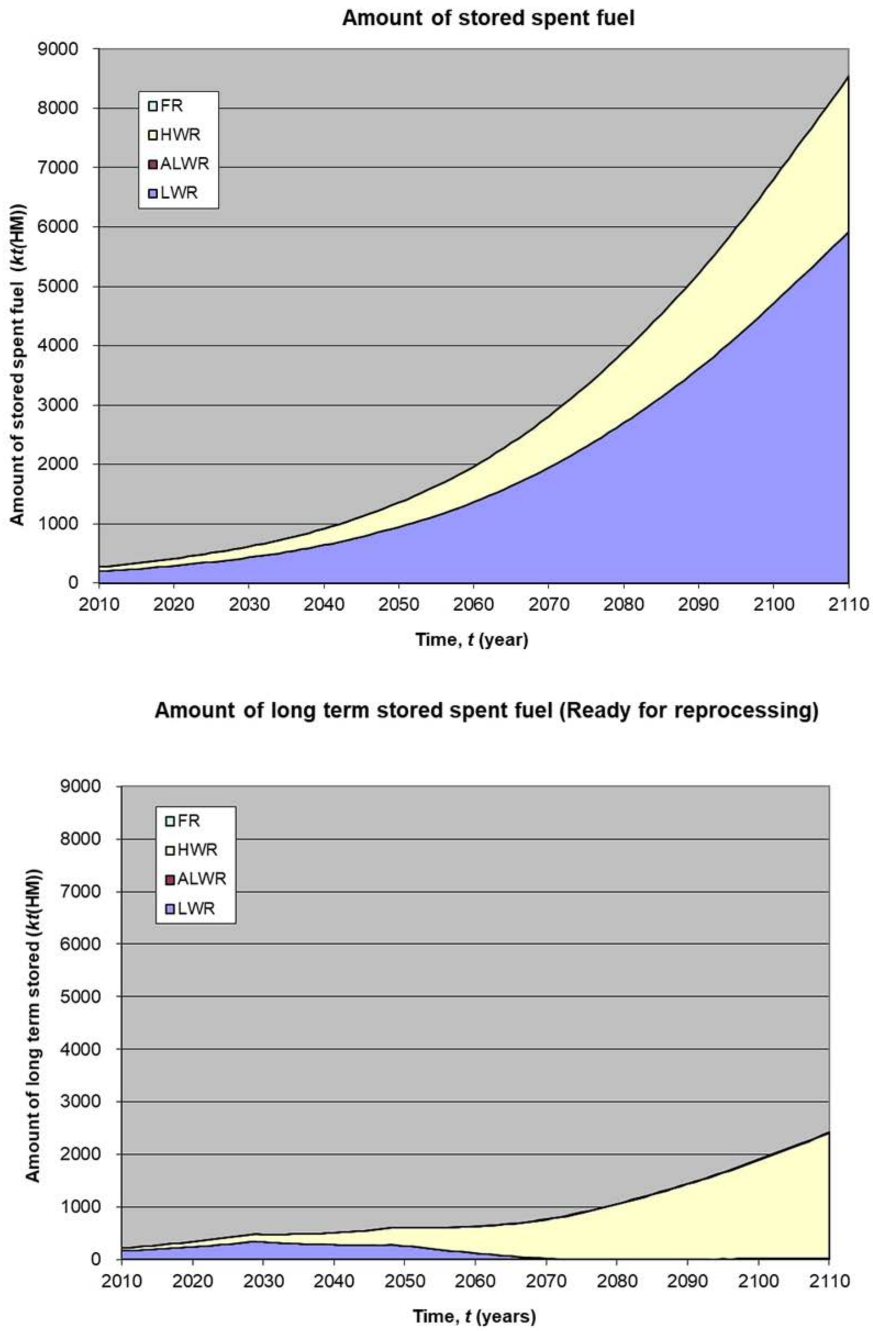


FIG. 5. Comparison of cumulative amount of spent fuel stored in two GAINS scenarios [9]. (Left) An NES based on thermal reactors only. (Right) An NES based on a combination of thermal and fast reactors.

enhance the efficiency and competitiveness of NESs. Consequently, INPRO launched the collaborative project SYNERGIES [10] as a follow-up of the GAINS project [9]. SYNERGIES defined ‘synergy’ as the “actions that a country or a group of countries undertake to facilitate (i.e. enable, accelerate and optimize) the deployment of an NES aiming at enhancing its sustainability” [10]. This includes the existing commercial trade of nuclear materials, equipment and services, and bilateral and multilateral arrangements or any new mechanisms for the sharing of nuclear technologies and facilities. Innovations in legal, regulatory and institutional set-up would be required to build up synergetic effects.

For the enhancement of NES sustainability, the SYNERGIES project focused on several issues that challenge the sustainability of NESs. The project identified that the following issues need to be addressed, and appropriate solutions need to be found through technical innovations and multilateral cooperation:

- The buildup of spent fuel that is creating a burden in the form of high level radioactive waste for future generations to manage;
- Ineffective use of natural fissile materials that might create problems of fissile resource availability;
- The presence of critical materials (e.g. plutonium) in directly disposed spent fuel that creates security and proliferation concerns;
- The heavy up-front investments required to develop and deploy innovative nuclear technologies, making them unaffordable for many potential users;
- Risks related to the global spread of sensitive technologies for uranium enrichment and spent fuel reprocessing.

In order to address these issues, the SYNERGIES project focused on material flow and economic assessments for the evaluation of different strategies leading to a holistic enhancement of NES sustainability at the national, regional and global levels. It also aimed at identifying and assessing the impediments to establishing different forms of collaboration in enhancing the sustainability of the NES globally. The project (2012–2014) was implemented with the participation of 24 countries and the Organisation for Economic Co-operation and Development's Nuclear Energy Agency. The diversity of the participating countries, which had different preferences regarding nuclear technologies and collaboration mechanisms, was one of the main strengths of the project.

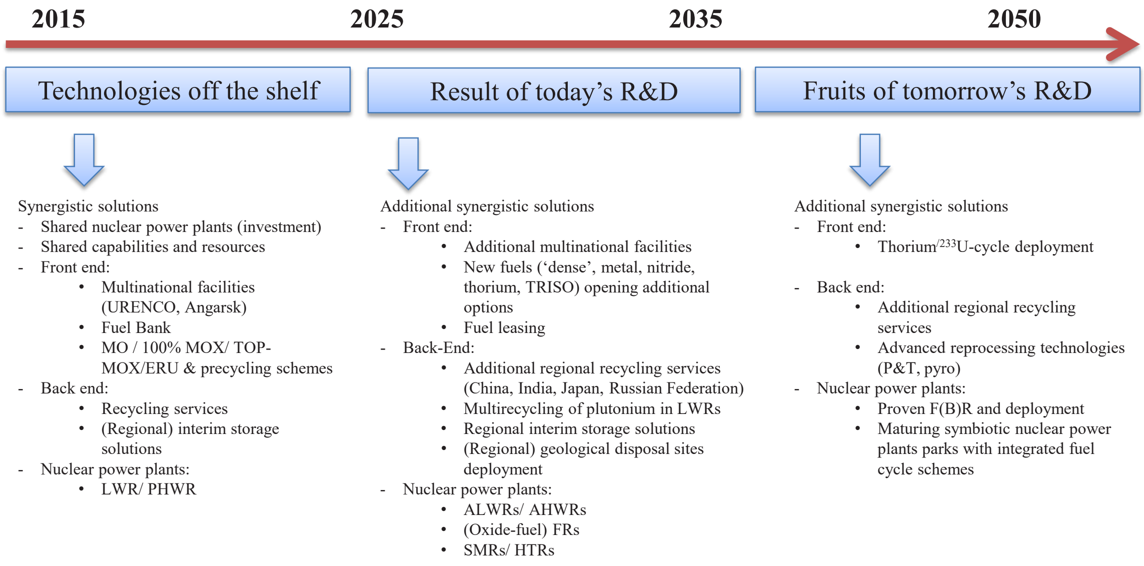
In addition to collaboration arrangements, the SYNERGIES project also addressed synergies in technologies. Technical synergies are defined as the technical combination of nuclear reactor and fuel cycle technologies that helps enhance NES sustainability. For example, one option to enhance sustainability could be recycling spent fuel from one type of nuclear reactor, after physical processing, and using it in another type. This option can help enhance sustainability by saving on natural uranium usage and reducing the spent fuel volume for final disposal. Another example of technical synergy that enhances NES sustainability is the use of MOX fuel, which involves a limited recycling of spent fuel with chemical reprocessing. This option also brings a saving in natural uranium usage and reduces the waste burden, while keeping the option of the future utilization of fertile materials open. A closed nuclear fuel cycle with thermal and fast reactors and complete recycling of spent fuel is the technical synergy that offers full utilization of the energy potential of nuclear materials and a large reduction in the long lived radiotoxicity burden of high level radioactive waste, while keeping sensitive materials (e.g. plutonium) out of the waste, thereby assuring a considerable enhancement of NES sustainability.

Altogether, 27 case studies have been performed under this project, covering 21 explicitly addressed technical synergies and 20 synergistic collaboration arrangements. These studies explored 12 possible cooperative solutions on regional or global levels. These case studies are built around a storyline developed for the project, shown in Fig. 6.

The SYNERGIES project concluded that a globally more sustainable NES can be progressively developed if information on innovative nuclear technologies and various nuclear energy facilities deployed in different countries is shared.

Such a synergistic approach would be beneficial for all collaborating countries, providing opportunities for exploiting economies of scale and achieving higher rates of capacity growth and capacity utilization. The cooperation among countries for R&D would also speed up the desired transition to an NES with enhanced sustainability.

Nonetheless, there are several challenges and impediments to realizing the potential benefits of synergies. The case studies identified that the slow pace of R&D of nuclear energy technologies and the limited usage of even more settled technologies such as MOX fuel are restraining the enhancement of NES sustainability. The technical and institutional contexts are not yet sufficiently developed and the motivations for collaboration in the fuel cycle back end are not always evident. Better understanding of the



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

FIG. 6. Storyline for scope of SYNERGIES case studies [10].

challenges and impediments and finding appropriate solutions to overcome them is critical to implement joint actions by countries to facilitate the deployment of the NESs with enhanced sustainability.

3.3. APPROACH TO THE COMPARATIVE EVALUATION OF NUCLEAR ENERGY SYSTEM OPTIONS AND SCENARIOS

Comparative evaluation is a process that helps weigh the merits and demerits of various options against key criteria identified as the main considerations for decision making. The process is rather simple when two or more options are being compared in terms of only one characteristic that is also measurable, for example, cost. It becomes more complex when the alternatives have to be rated in terms of several characteristics that are of different natures, some of which may not be objectively quantifiable. At a dynamic system level, the complexity of comparative evaluation is further compounded. In such situations, it is necessary to take a systematic approach that facilitates the comparison of alternatives in terms of each of the selected aspects followed by the aggregation of the results of all the aspects to determine the overall rank of each alternative. The approach could be used for comparisons of the performance and dynamics of steady state systems under different scenarios.

INPRO implemented a collaborative project, KIND, to develop guidance and tools for comparative evaluations of the status, prospects, benefits and risks associated with the development and deployment of innovative nuclear technologies [11]. The project was implemented in 2014–2017 by experts from Armenia, Bulgaria, China, Croatia, France, Germany, India, Indonesia, Malaysia, Romania, Russian Federation, Thailand, Ukraine, UK, USA and Viet Nam as participants or observers in the project's different tasks.

Within the KIND project, a number of trial case studies have been performed involving the comparative evaluation of NES deployment scenarios, hypothetical NES options and NESs based on the different reactor technologies as well as nuclear and non-nuclear energy systems.

The KIND approach is applicable to a range of comparative evaluations starting from the comparison of alternatives at the technology level, followed by the system level and then by the system evolution over a long term period. The KIND comparative evaluation approach follows a systematic process spread over several sequential steps with feedback at different stages, as depicted in Fig. 7.

At the start of the KIND comparative evaluation process, interaction among decision makers, experts and other main stakeholders is very important. This helps identify the main issues related to the NES that are critical for decision making in a particular country's situation. The next step, the formulation of alternatives, is intended to identify the technology options and the factors or driving forces that influence system performance and evolution. At this stage, key indicators that would help evaluate the merits and demerits of each NES should be identified. The selection of key indicators should also be based on their measurability and the availability of data and analytical tools for their computation.

The next stage is the evaluation of the selected key indicators for each of the NES options or scenarios and the application of a suitable methodology for calculating the overall rank of each option or scenario by aggregating the key indicators using experts' judgement and decision makers' preferences.

Scenarios, particularly those developed with computer based modelling and simulation, produce a large amount of quantitative information. The performance of the system under one scenario may be much better compared with its performance under another scenario in terms of one consideration or factor, while being less desirable in terms of another aspect or factor. When a number of factors are involved and they do not all have a common measurable metric, the overall rank of an alternative cannot be determined. The KIND approach, therefore, employs multicriteria decision analysis techniques for comparing and evaluating innovative nuclear technologies, NES options and alternative strategies and scenarios. Multicriteria decision analysis techniques are well developed and widely used for supporting decision making in almost all disciplines. The KIND approach has been implemented in the form of a toolkit for comparative evaluation under the INPRO project. The approach also takes into account the lessons learned and the best practices for supporting decision making [28].

Uncertainty is inherent in any consideration of future evolution. NESs face the same challenge. Setting aside the political uncertainties, there are large technical uncertainties in the outcome of R&D efforts and the availability of innovative technologies, their performance, and the effectiveness of cooperative arrangements. The KIND approach has paid special attention to sensitivity and uncertainty analyses. Owing to the subjective valuation of some of the key indicators or weighting factors for their aggregations, uncertainties can be dealt with using a range of possible valuations by different experts.

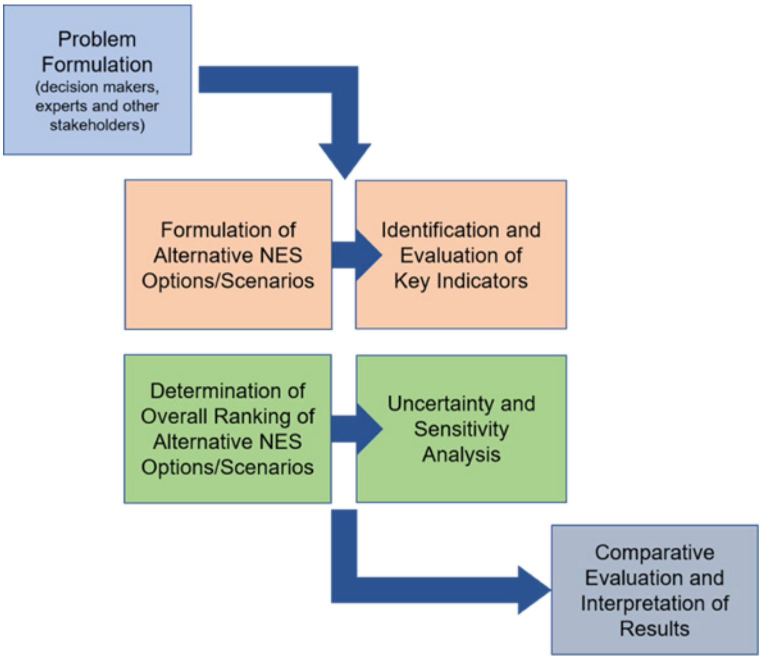


FIG. 7. The scope of the KIND approach for comparative evaluation.

The KIND approach has been applied extensively for comparative evaluations of various NES options at the scenario and technology levels, comparisons of nuclear fuel supply and waste management options, and for the examination of cross-cutting issues that demonstrate the potential of the KIND approach for decision support within a wide landscape of different practical nuclear engineering problems requiring expert judgement aggregations. Within the INPRO project, a number of quantitative numerical case studies were carried out on comparative evaluations of NES deployment scenarios, hypothetical NES options and on NESs based on pressurized water reactors, HWRs, sodium cooled fast reactors, lead cooled fast reactors, molten salt reactors and accelerator driven system reactor technologies. Case studies were also developed for non-nuclear energy technologies to demonstrate the applicability of the KIND approach [29]. As a follow-up to KIND, INPRO initiated a collaborative project, Comparative Evaluation of Nuclear Energy System Options. Its objective is to apply the KIND approach in case studies involving the comparative evaluation of NES options and scenarios. The case studies are being performed by interested INPRO members to exercise the utility of the comparative evaluation approach to support decision analysis and prioritization in national nuclear energy programme development.

It has been found that the KIND approach could be very useful for the evaluation of different aspects of NES options or scenarios focusing on NES sustainability objectives, for example, aspects in the areas of economics, resources, proliferation resistance, waste management and so on. The approach could be very effective in comparing the role of different technology innovations in enhancing the sustainability of the overall NES. Such comparative evaluations help comprehend and explain the benefits of different alternatives and foster a productive dialogue among the stakeholders, leading to sound decision making [11].

3.4. TEMPLATE FOR ROAD MAPPING TOWARDS ENHANCED NUCLEAR ENERGY SUSTAINABILITY

The INPRO collaborative projects GAINS, SYNERGIES and KIND generated a multitude of data and information that helped develop insight into the challenges in the development of sustainable NESs and provided a host of recommendations on the efforts needed in technology innovation and international cooperation for enhancing the sustainability of global, regional and national NESs. It was recognized at the 11th INPRO Dialogue Forum that to operationalize these recommendations and enhance the sustainability of the global NES, concrete actions and work plans with time frames are needed. While several countries are pursuing the development of innovative nuclear reactors and fuel cycles, and there are several initiatives for international cooperation for developing sustainable NESs, practical actions at the national, regional and global levels can be taken if detailed plans and roadmaps are elaborated, discussed and agreed. In order to help develop such plans and understand their costs, risks and benefits, a systematic framework is needed.

Building upon the experience and methodological frameworks of the GAINS, SYNERGIES and KIND projects, INPRO implemented another collaborative project, Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems (ROADMAPS). The idea was to integrate the results of GAINS, SYNERGIES, KIND and several other INPRO studies, and create a template that can be used for developing roadmaps for a transition to more sustainable NESs. Figure 8 shows the interconnections among these collaborative projects.

The main objective of the ROADMAPS project was to develop a structured approach for facilitating the development of nuclear energy roadmaps [30]. It aimed at putting together a template representing an approach for elaborating actions, scopes of work, time frames for maintaining and enhancing the global sustainability of nuclear energy, and providing models for international cooperation and frameworks for collaborative efforts by various stakeholders.

The approach and the roadmap template allow the bottom-up integration of national roadmaps to derive a regional or global pathway towards enhanced nuclear energy sustainability (Fig. 9).

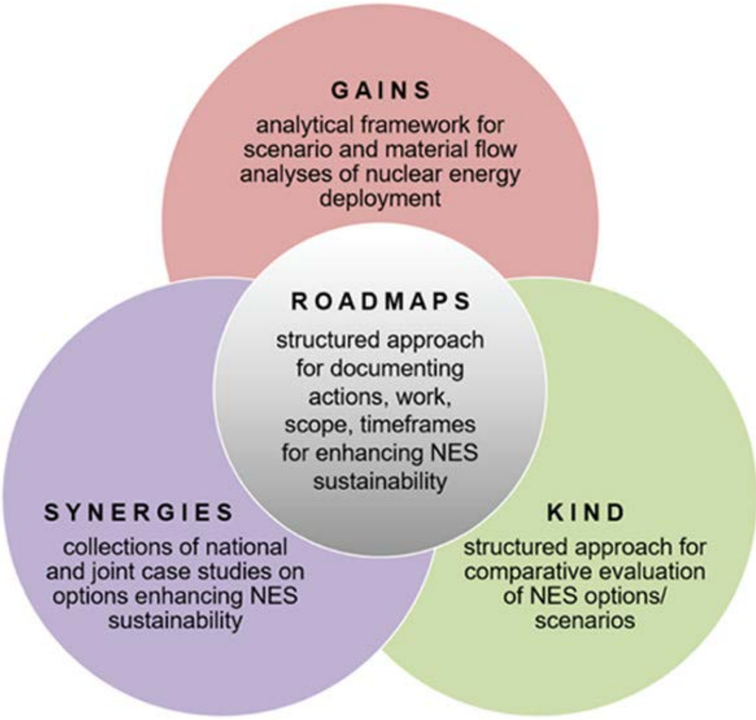


FIG. 8. Interconnections of the INPRO collaborative projects.

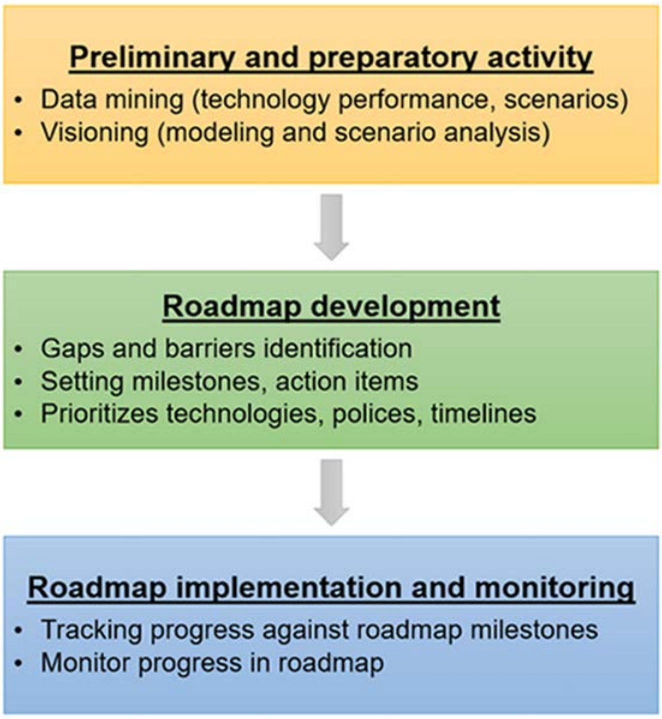


FIG. 9. General road mapping flow chart.

A spreadsheet based ROADMAPS tool (ROADMAPS-ST) has also been developed for supporting the application of this approach [30]. ROADMAPS-ST offers a framework for assembling a roadmap for a sustainable NES by connecting various elements consistently within a country and beyond. It also helps in the analysis and visualization of the results.

The ROADMAPS project defined a process for developing roadmaps. It starts with a preparatory stage covering the compilation of data on the technical and economic performance of nuclear technologies, the main characteristics of alternative options and scenarios, the resulting NESs and the possible international and regional collaboration frameworks. The next stage is roadmap development, which aims at setting the targets and milestones, spotting gaps and barriers, and identifying action items with corresponding timelines. At this stage, several alternative roadmaps can be prepared reflecting different priorities, policies and timelines.

Once a national roadmap has been finalized, the final stage is roadmap implementation and monitoring. As the action items of the finalized roadmap are implemented, a monitoring system with suitable indicators can be used to track progress against milestones and targets, and corrective measures suggested in case of deviations. The roadmap document may include an action plan for implementing the roadmap and taking corrective measures and actions.

While preparing a roadmap, a long term perspective of the evolution of an NES should be taken. The dynamic nature of the deployment process, the multiplicity of technology choices, and the conflicting character of various requirements and uncertainties should be reflected in the analysis. Sometimes, the process may suggest contradictory actions to fill the identified gaps and meet the identified challenges. The analysis and visualization feature of ROADMAPS-ST will help resolve conflicts and smooth out a practicable roadmap for national implementation.

The road mapping process can elaborate options for technology infrastructure, including institutional mechanisms and economic and financial arrangements that would lead towards enhanced nuclear energy sustainability. The process can also indicate opportunities for savings in time, efforts and resources.

Countries with a small nuclear energy programme or those considering the introduction of nuclear energy would need a close collaboration with the technology holder countries or among themselves. In some cases, of the limited availability of uranium resources would mean turning to resource rich countries. In others, a limited local industrial capability would necessitate collaborating with industrially advanced countries. There could be a need for sharing facilities to minimize costs arising from economies of scale and other factors. Both the existing and new possibilities, whether commercial or cooperative, should be considered in the road mapping approach. The comparative evaluation of international and regional cooperation options would be very useful for these countries. They can identify possibilities for minimizing national efforts on nuclear infrastructure development, including spent fuel storage and disposal. With this evaluation, the countries can compare potential cooperation schemes and identify the best option for each case.

Since the overall objective is to enhance the global sustainability of an NES, the roadmap template allows the integration of country level roadmaps into regional roadmaps and finally global roadmaps that provide guidelines for the collaboration arrangements necessary for maintaining and enhancing NES sustainability. This approach can also be used for the strategic planning and management of NES development at the national, regional and global levels.

The proposed road mapping approach can be seen in connection with the INPRO methodology, closely linked with the areas of INPRO assessment — infrastructure, safety, economics, waste management, proliferation resistance and the environment. The goals and targets for a roadmap can be aligned with the INPRO methodology's basic principles for each of these areas, as shown in Table 1.

TABLE 1. ALIGNING ROADMAP TARGETS WITH THE BASIC PRINCIPLES OF INPRO METHODOLOGY

Basic principles of the INPRO methodology [12–16]	Example roadmap targets
Infrastructure	
“A 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” [13].	Nuclear infrastructure is optimized taking into account domestic resources and opportunities of international cooperation.
Safety	
“Installations of an Innovative Nuclear Energy System shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations” [12].	The defence-in-depth is enhanced through broad incorporation of the inherent safety and reliable passive safety features.
Economics	
“Energy and related products and services from NESs shall be affordable and available” [14].	Comparable or best economic performance in the energy sector is achieved.
Nuclear waste management	
“Radioactive waste in an [innovative NES] shall be managed in such a way that it will not impose undue burdens on future generation” [12].	A final end state for each category of radioactive waste that would require no safety or safeguards measures to be implemented by future generations is defined.
Proliferation resistance	
“Proliferation resistance intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that [they] will continue to be an unattractive means to acquire fissile material for a nuclear weapons program. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself” [12].	Safeguards agreement and additional protocol are signed and ratified. Low attractiveness for the acquisition of fissile material of nuclear materials and nuclear technologies is ensured. A balance of production and consumption of fissile material in the fuel cycle is achieved.
Environment	
“The expected adverse environmental effects of an NES should be well within the performance envelope of current NESs delivering similar energy products” [15]. *“The NES shall be capable of contributing to the energy needs in the twenty-first century while making efficient use of non-renewable resources” [16].*	Environmental risks are at a level of the best energy sector technologies. Full use of the energy potential of fissile materials is achieved.

4. SCENARIO ANALYSIS AND DECISION SUPPORT TOOLS

Under the umbrella of the INPRO project, a set of comprehensive and technically sound scenario analysis and decision support tools has been created to facilitate the development of national nuclear energy programmes and strategies and NES alternatives and scenarios. This set of scenario analysis and decision support instruments includes computer based models and analytical tools that allow the quantified evaluation of technology alternatives for an NES, taking into consideration all the main aspects of sustainability — economics, safety, environment, waste management, proliferation resistance and infrastructure. These scenario analysis and decision support tools have been used for major INPRO studies at global and regional levels as well as for several national studies under INPRO collaborative projects [9–11, 30].

These tools are briefly described in the following sections. They can collectively provide a systematic configuration for the comprehensive evaluation of NES options and scenarios. For example, the Nuclear Economics Support Tool (NEST) allows the preliminary assessment of specific economic parameters and financial figures of merit (levelized unit of electricity cost, internal rate of return, return of investment, net present value, total investment) for various reactor technologies at the plant level that are being considered as candidates for deployment in the national NES. The MESSAGE-NES tool can be used to model and evaluate nuclear energy deployment scenarios with varying assumptions about the potential role of innovative technologies. The KIND Evaluation Tool (KIND-ET) then takes the scenario analysis results in terms of economics, technical performance, resource use, proliferation resistance and so on and ranks the NES options and scenarios. All these results can then be used to construct roadmaps for elaborating deployment schemes using ROADMAPS-ST. Depending upon the scope of the evaluation study, these tools can be used individually or combined to achieve a comprehensive evaluation.

4.1. NUCLEAR ECONOMICS SUPPORT TOOL

Economics is one of the INPRO methodology areas of NES sustainability assessment. To achieve the goal of the basic principle in the area of economics: "energy and related products and services from [an innovative NES] must be affordable and available" [12], four user requirements have been set as targets for this area.

(i) The cost of products from an NES should be competitive with that of alternative energy sources.
(ii) The total investment in an NES should be such that the funds could be raised by the country in question.
(iii) The risk of investment of an NES should be acceptable to investors.
(iv) The innovative NESs should be compatible in meeting the requirements of different markets.

NEST is being used in the IAEA's NESA service to Member States; however, it was also found useful in a number of global scenario studies performed within INPRO projects, such as in the GAINS and SYNERGIES collaborative projects.

In order to perform the economic evaluation for verifying whether the NES under consideration fulfils the above mentioned user requirements in this area, a suitable analytical tool was needed. The IAEA, as part of the INPRO project, developed the NEST to help perform necessary cost calculations. It can calculate a number of metrics for economic assessment, for example, levelized unit electricity cost, net present value, internal rate of return and return on investment.

Like any other analytical tool, NEST needs certain input data to calculate the above mentioned metrics. These include estimates for the quantum and timings of all the expenditures and revenues for the proposed NES. The following data are input, avoiding any duplication of costs whatsoever:

- Capital cost with details of overnight capital cost, capital investment schedule, interest during construction, back-fitting cost and decommissioning cost.
- Operating cost with details of fixed and variable operation and maintenance cost, including waste management cost, taxes and so on.
- Fuel cost with details of entire fuel cycle costs — natural uranium cost, conversion cost, enrichment cost, fuel fabrication cost and back end costs such as spent fuel storage, reprocessing, disposal and so on. For fuel cost calculations, additional information is needed, such as enrichment level of first core and reloads, core power density, losses of nuclear materials at each fuel cycle step.
- Technical parameters such as net electric output, net thermal efficiency, average load factor, construction time and plant life are also needed.

The main outputs of NEST are levelized unit electricity cost, net present value, internal rate of return and return on investment. Nuclear technologies can be compared with alternative energy sources using these indicators. Since there are large uncertainties in some of the inputs, NEST allows for sensitivity and uncertainty analyses for establishing the competitiveness of the proposed NES. The input values for various parameters can be chosen within technically feasible and economically viable ranges in regard to the selected metric. Figure 10 shows the results of an uncertainty analysis for the comparison of an NPP and a coal power plant performed in a Thailand case study in which NEST was used [11].

Since various existing and innovative nuclear reactors and their respective fuel cycles have very specific technical characteristics, for example, the use of enriched fuel for LWRs, or of heavy water for HWRs, NEST includes all the necessary technical details for a number of reactor types and their fuel cycles. The cost calculations are also dependent on the scope and coverage of the fuel cycle, for example,

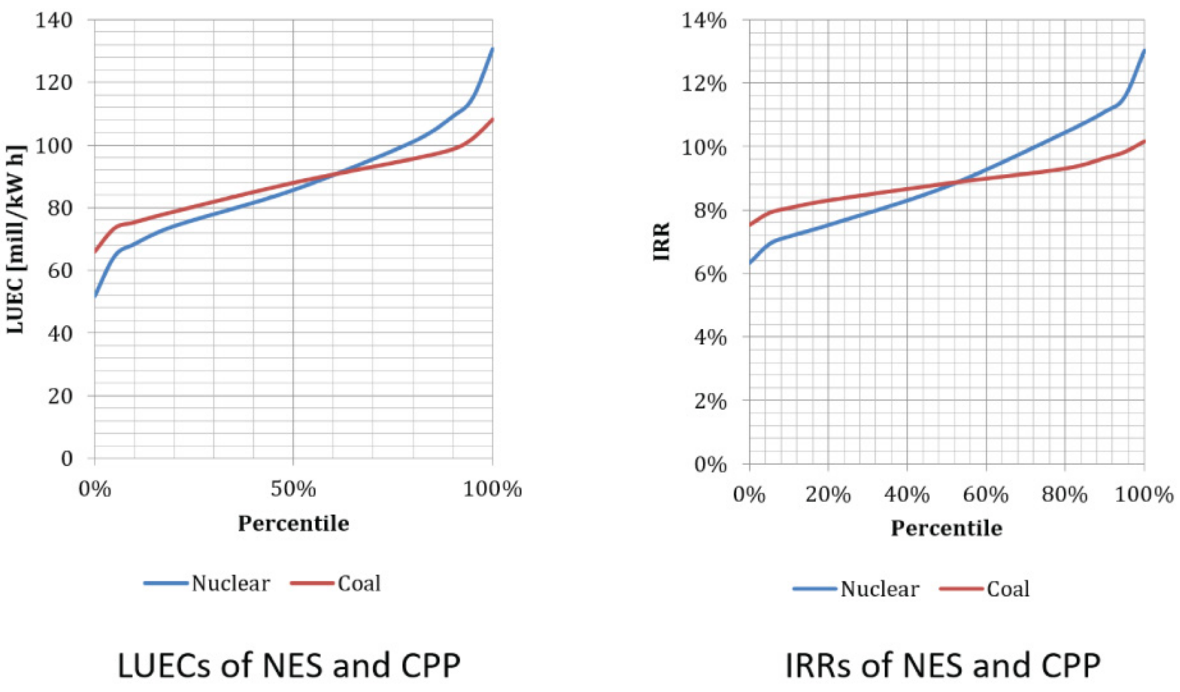


FIG. 10. Results of uncertainty analysis of levelized unit electricity cost (labelled LUEC) and internal rate of return (labelled IRR) for nuclear and coal power plants. N.B. A percentile is a statistical measure of distribution representing the area under the curve of a distribution. It is the level below which a certain percentage of the data falls.

whether it involves a once-through fuel cycle, the recycling of plutonium and uranium as MOX fuel, or a closed fuel cycle. NEST includes all the details of the front ends and back ends of the various fuel cycles. The following NES options are included in NEST:

- HWRs with once-through fuel cycles;
- LWRs with once-through fuel cycles;
- LWRs using MOX fuel with reprocessing of spent fuel and multirecycling of plutonium and uranium;
- Fast reactors with a closed fuel cycle in equilibrium (i.e. the production and consumption of plutonium is in equilibrium in the NES);
- Fast breeder reactors with a given breeding ratio in a closed fuel cycle;
- Equilibrium NES with thermal and fast reactors.

The details of various NESs included in NEST and its calculation methodology are documented in Ref. [14]. INPRO has established a close collaboration with the Generation IV International Forum Economic Methodology Working Group, and exchanges experiences with the group on the economic assessment of NESs. The computations of NEST have been validated by comparing its results with other similar tools such as the Generation IV International Forum economic model G4-ECONS. The results were found to be in excellent agreement for the same sets of input data.

4.2. MODELLING OF NUCLEAR ENERGY SYSTEMS WITH MESSAGE

MESSAGE was originally developed at IIASA for its global energy studies [31]. The model was acquired by the IAEA and enhanced for supporting capacity building activities in Member States for energy and nuclear power planning [3]. It is basically a technology oriented, system engineering model that combines the technical, economic and environmental performance of different energy supply and use technologies and optimizes system-wide performance over the medium to long term. It has been extensively used at global, regional and national levels for developing scenarios to support energy planning and policy analysis.

MESSAGE-NES is an adapted and enhanced version of the model that has been used in various INPRO studies [32]. Based on experience with the model for INPRO studies under its major projects such as GAINS and SYNERGIES, MESSAGE-NES has been included in INPRO's scenario analysis and decision support toolkit. It provides a convenient platform for modelling complex NESs and for developing alternative scenarios of the dynamic evolution of the system. It helps evaluate trade-offs between various aspects of sustainability of an NES. Figure 11 shows the MESSAGE representation of a simple energy system and of the details of an NES. Depending upon the scope of the study, the NES can be represented on an aggregated level or with full details of the associated nuclear fuel cycle.

MESSAGE-NES includes calculations of dynamic mass flows across the nuclear fuel cycle, including natural resource depletion, spent fuel and radioactive waste accumulation and specific material inventories. As for the comparison of alternatives, the user can define the selection criterion — the objective function. For example, it is possible to focus on economic performance by using cost minimization as the main criterion, to address environmental and public risks by using minimization of radioactive waste accumulation as the main criterion, or to consider non-proliferation concerns by minimization of inventories of critical materials like plutonium as the main criterion. It is also possible to combine various criteria by assigning weights to each of them and optimizing the overall system evolution.

The main outputs of the model include an optimized deployment plan for various nuclear technologies, including details of (a) the sizes and timings for building various facilities and services of an NES; (b) material mass flows, inventories, resource depletion and accumulated radioactive wastes; and (c) investment and operating costs.

The main features and capabilities of MESSAGE-NES are documented in the MESSAGE-NES User Guide [32], which also provides detailed guidance on the modelling of specific technical and

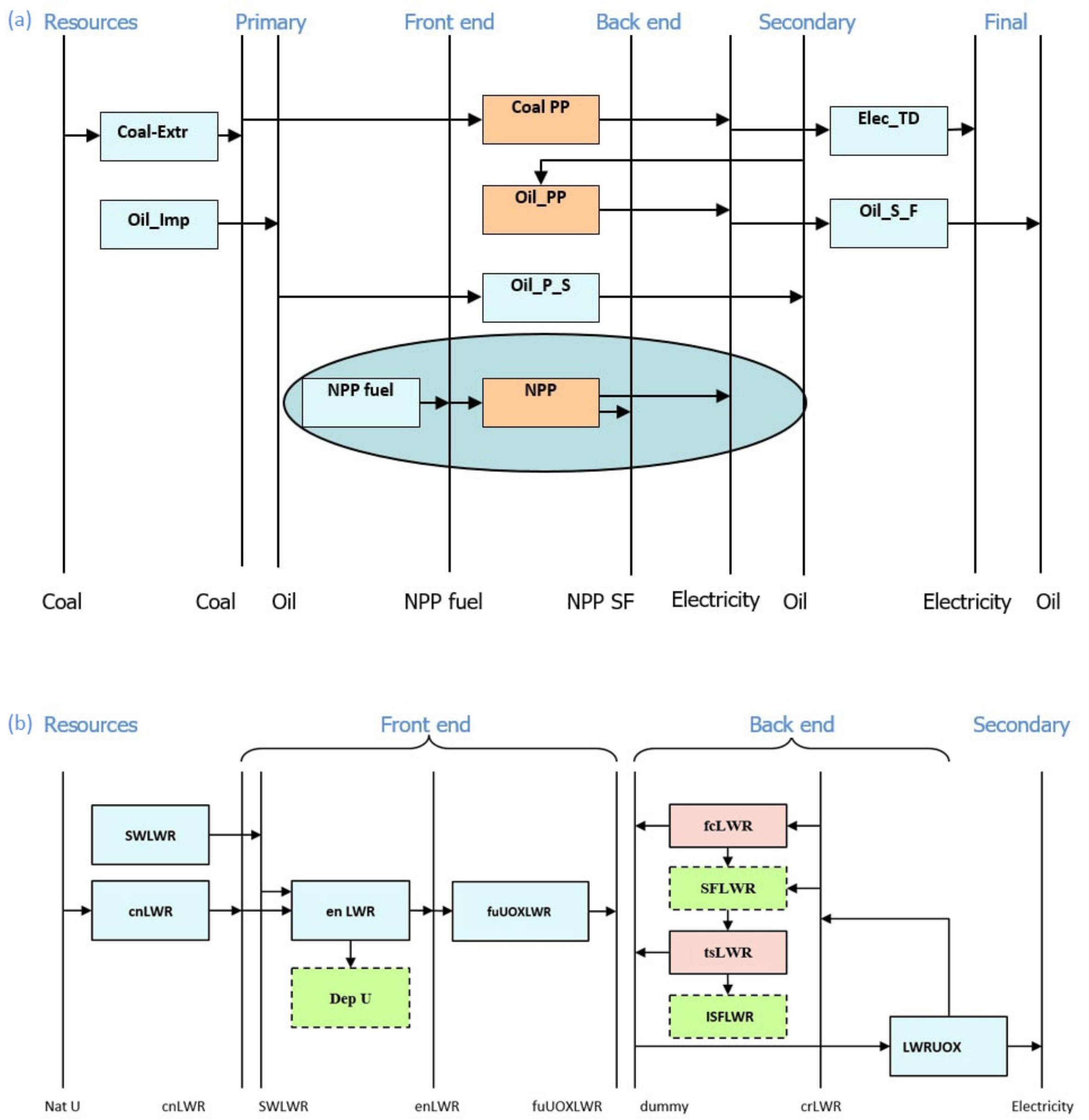


FIG. 11. MESSAGE representation of (a) a simple energy system, including nuclear technology, and (b) nuclear power with details of the nuclear fuel cycle. Legend: cnLWR — conversion of uranium for LWR fuel; Coal-Ext — coal extraction; Coal PP — coal-fired power plant; crLWR — dummy form needed to model discharged fuel transfers to and between storage; Dep U — depleted uranium; dummy — dummy back-stop technology; Elec_TD — electricity transmission and distribution; enLWR — enrichment of uranium for LWR fuel; fcLWR — auxiliary technology to put discharged LWR fuel into cooling storage; fuUOXLWR — uranium oxide fuel fabrication for LWR; ISFLWR — interim dry storage for LWR spent fuel; LWRUOX — LWR operating on uranium oxide fuel; Nat U — natural uranium; Oil_Imp — oil import; Oil_PP — oil power plant; Oil_P_S — oil processing and supply; Oil_S_F — oil secondary to final; SF — spent fuel; SFLWR — cooling storage for LWR spent fuel; SWLWR — separative work for LWR fuel; tsLWR transport of LWR spent fuel from cooling storage to ISFLWR.

economic aspects of various nuclear reactor technologies and their respective fuel cycle facilities. Three demonstration cases are also presented: (i) an NES based on once-through fuel cycle for LWRs and HWRs; (ii) an NES based on a partly closed fuel cycle for LWRs and HWRs, with recycling of recovered uranium and plutonium in the form of MOX fuel for LWRs; (iii) an NES based on a fully closed fuel cycle, with multiple recycling of plutonium from thermal and fast reactors. These cases can be used as the starting point for national experts to elaborate their own system level models of national NESs using MESSAGE-NES.

The application of MESSAGE-NES to a variety of country case studies is documented in Ref. [33]. For example, an Argentinian case study modelled an NES with a once-through fuel cycle and HWRs considering existing and possible future facilities. This case study explored the advantage of building local fuel cycle facilities and their optimal timings and sizes as nuclear electricity generation increases in future. The case study also determined the nuclear material requirements, inventories and waste accumulation. The representation of the Argentinian NES in MESSAGE-NES is shown in Fig. 12.

Another example of NES modelling in MESSAGE-NES is a case study of China for an NES based on thermal and fast reactors in a closed nuclear fuel cycle. The complex material flow in this system was represented in MESSAGE-NES, as shown in Fig. 13.

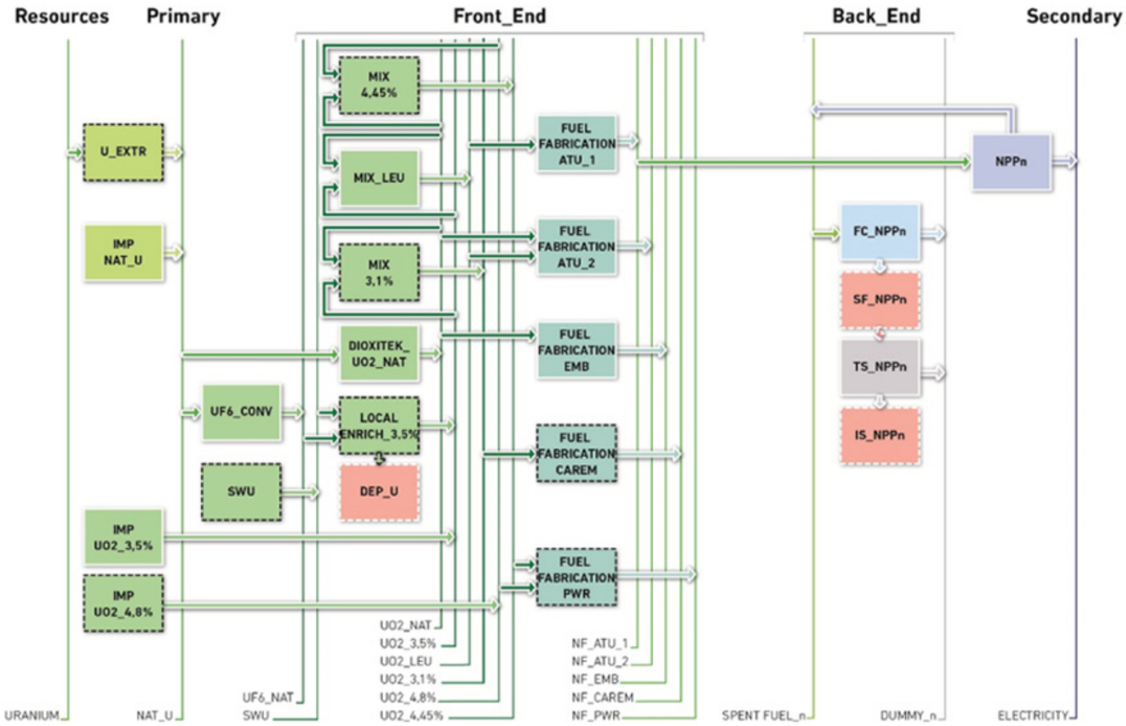


FIG. 12. MESSAGE-NES representation of the NES based on HWRs in the once-through nuclear fuel cycle from the Argentinian case study. Legend: ATU_1 —Atucha I NPP; ATU_2 —Atucha 2 NPP; CAREM —small modular reactor CAREM; DEP_U — depleted uranium; DIOXITEX_UO2_NAT — natural enrichment uranium dioxide from local supplier Dioxitek S.A.; DUMMY_n — dummy back-stop technology; EMB — Embalse NPP; FC_NPPn — fuel cycle for n-th NPP; IMP NAT_U — imported natural uranium; IMP UO2_3.5% — imported UO2 with 3.5% enrichment; IMP UO2_4.8% — imported UO2 with 4.8% enrichment; IS_NPPn — intermediate storage of spent fuel for n-th NPP; LOCAL ENRICH_3.5% — local enrichment 3.5%; MIX 3.1%, MIX 4.45%, MIX_LEU — different considered variants of fuel mix for different reactors (natural uranium is mixed with enriched uranium in certain proportions); NAT_U — natural uranium; NF — nuclear fuel; NPP — nuclear power plant; PWR — pressurized water reractor; SF_NPPn — spent fuel n-th NPP; SPENT FUEL_n — spent fuel of n-th NPP; SWU — separative work units; TS_NPPn — transport of spent fuel from cooling storage to intermediate dry storage; U_EXTR — uranium extraction; UF6_CONV — conversion to UF6; UF6_NAT — UF6 with uranium of natural enrichment; UO2_ x.y% — uranium dioxide fuel of x.y% enrichment; UO2_LEU — uranium dioxide fuel. based on low-enriched uranium.

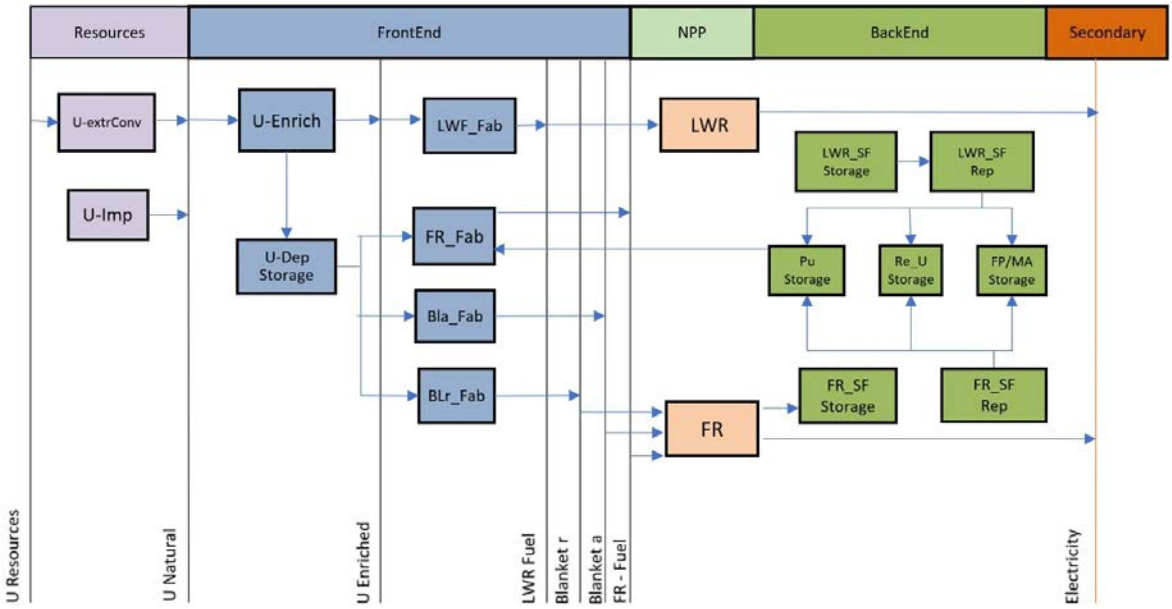


FIG. 13. MESSAGE-NES representation of an NES with a closed nuclear fuel cycle and thermal and fast reactors for a China case study. Legend: Bla_Fab — fabrication of fuel for axial blankets; BLr_Fab — fabrication of fuel for radial blankets; FP/MA Storage — storage for fission products/minor actinides; FR — fast reactor; FR_Fab — fabrication of fuel for fast reactors; FR-Fuel — fast reactor fuel; FR_SF Rep — spent fuel repository for fast reactors; FR_SF Storage — spent fuel storage for fast reactors; LWF_Fab — fabrication of fuel for light water reactors; LWR_SF Rep — spent fuel repository for LWR; LWR_SF Storage — spent fuel storage for LWR; Re_U Storage — reprocessed uranium storage; U-Dep Storage — depleted uranium storage; U-Enrich — uranium enrichment; U-extrConv — uranium extraction and conversion; U-Imp — imported uranium.

4.3. COMPARATIVE EVALUATION OF NUCLEAR ENERGY SYSTEMS WITH KIND-ET

The decision support tool KIND-ET was developed under the INPRO collaborative project KIND [11]. This tool is intended to support the comparative evaluation of NES options and scenarios. It employs multiattribute value theory for the comparison and ranking of the alternatives. The main attributes relevant to the sustainability of an NES are identified and quantified and, using experts' judgement and decision makers' preferences, the overall rank of NES options and scenarios is determined. The overall rank of an NES option or scenario is built in KIND-ET with a multi-level objectives tree using a number of key indicators and subindicators for various attributes or evaluation areas, as shown in Fig. 14.

KIND-ET uses single-attribute value functions to quantify the key indicators and/or subindicators for each of the evaluation areas and an additive multi attribute value function to calculate the overall score of each NES option or scenario, using experts' judgement and decision makers' preferences. The tool is developed as a spreadsheet based template that can be modified or adjusted according to the scope of an evaluation task and the structure of an NES.

For example, the weighting factors for a three level objective tree can be organized in KIND-ET, as shown in Fig. 15. In this case, the high level objectives are identified as cost, performance and acceptability. For each of these high level objectives, the INPRO areas of evaluation are specified and finally, for each of the evaluation areas, suitable indicators are selected. The next step is assigning weights to components at each level using experts' judgement and decision makers' preferences.

The quantitative estimates for each indicator have to be prepared to develop the overall ranking of the NES options or alternative scenarios. A consistent input data set for all the alternatives should be prepared with the help of common methodologies and tools such as MESSAGE-NES, NEST and others.

There are large uncertainties in the quantitative estimates of the key indicators, the value functions of various attributes and the weighting factors representing experts' judgement and decision

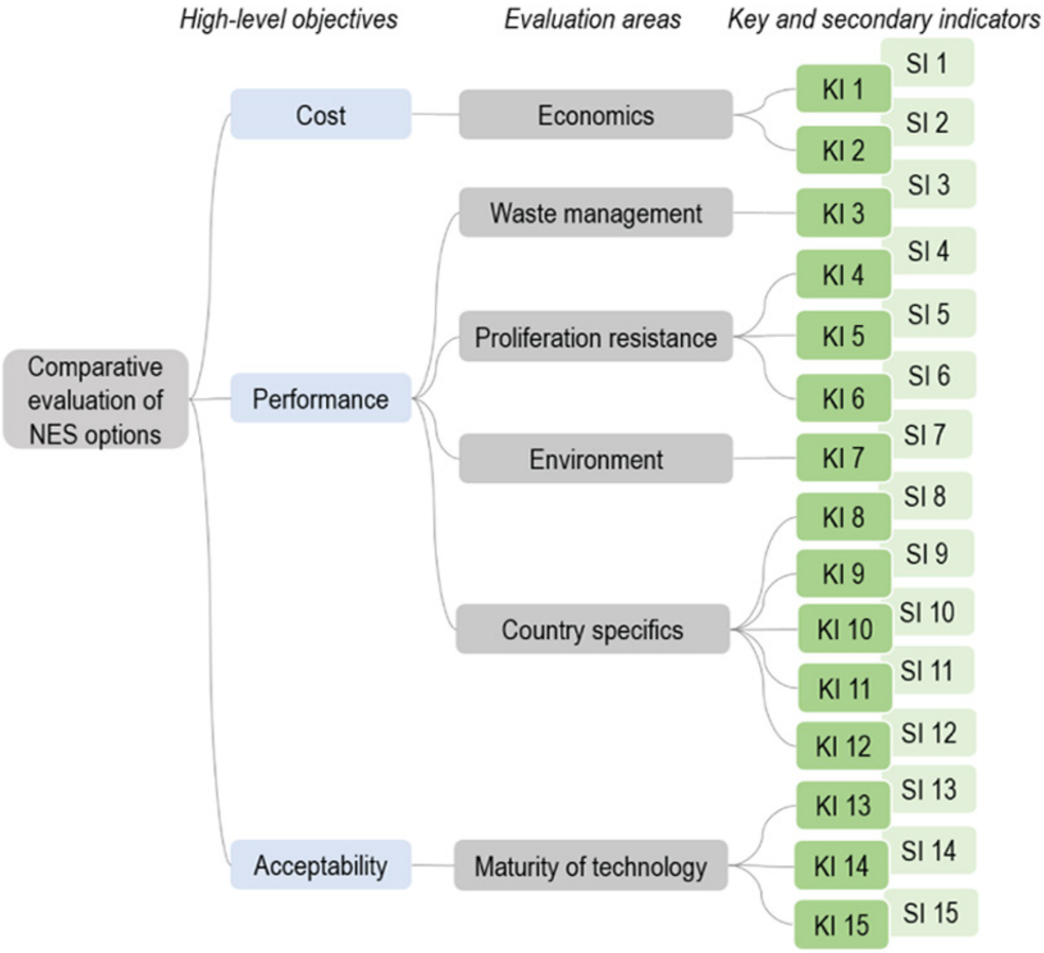


FIG. 14. Example of an objectives tree [11].

High-level objectives titles	High-level objectives weights	Areas titles	Areas weights	Indicators abbr.	Indicators weights	Final weights
Cost	0.300	Economics	1.000	E 1	0.800	0.240
				E 2	0.200	0.060
Performance	0.500	Waste management	0.100	WM 1	1.000	0.050
		Proliferation resistance	0.200	PR 1	0.100	0.010
				PR 2	0.200	0.020
				PR 3	0.700	0.070
		Environment	0.400	ENV 1	1.000	0.200
		Country specific	0.300	CS 1	0.100	0.015
				CS 2	0.200	0.030
				CS 3	0.300	0.045
				CS 4	0.300	0.045
				CS 5	0.100	0.015
Acceptability	0.200	Maturity of technology	1.000	M 1	0.200	0.040
				M 2	0.300	0.060
				M 3	0.500	0.100

FIG. 15. Assignment of weights to various components at different levels of an objectives tree.

makers' preferences. The choice of input data sets used for comparisons of alternative NES options or scenarios would significantly influence the results. Extensive sensitivity and uncertainty analyses should be performed to capture the uncertainties in the quantitative estimates. KIND-ET and its functional extensions developed in the Comparative Evaluation of Nuclear Energy System Options project[4] allow the convenient performance of sensitivity and uncertainty analyses in regards to weights, key indicators and single-attribute value functions as well as the enhancement of the quality of the represented results.

The mathematical methods and computations in KIND-ET have been validated with the help of a number of numerical examples of comparisons of both NES options and scenarios [11]. Figure 16 b shows the application of KIND-ET in an Armenian study performed under the KIND collaborative project. This study compared five different nuclear technology options and a no-nuclear option in terms of cost, performance and acceptability. The multilevel objectives tree and the results of the overall ranking of the alternatives are shown in Fig. 16 a.

Another example is presented in Fig. 17, which shows the application of KIND-ET for a comparison of the GAINS scenarios.

KIND-ET is a user friendly, problem oriented tool that offers the possibility of modification and adaptation to suit a specific application or advancements in methodological approach to comparative evaluation. For easier comprehension of the results, it offers a graphical and tabular display that can be customized by users. KIND-ET software can also be linked with other programs such as MS-Office and web based applications for data exchange and remote access.

4.4. ROAD MAPPING FOR ENHANCED NUCLEAR ENERGY SUSTAINABILITY WITH ROADMAPS SPREADSHEET TOOL

ROADMAPS-ST is a spreadsheet based tool developed by INPRO to facilitate application of its roadmap template and is described in Fig. 18. It is an analytical tool for supporting decision making on the deployment of NESs at national, regional and global levels. The tool is mainly driven by information prepared by experts, including data on technical and economic performance, and international collaboration mechanisms. It has been developed to support interested Member States in their efforts in developing national roadmaps and integrating them to form regional and global roadmaps. It uses Gantt charts to illustrate timelines for national, regional and global actions to maintain and enhance NES sustainability.

ROADMAPS-ST has been developed based on (a) the recommendations of the INPRO Dialogue Forum 11, Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems, held in October 2015; and (b) inputs from the participants and observers of the ROADMAPS collaborative project. The structure of INPRO's roadmap template is embedded in this tool. It is an open source, flexible and user friendly tool. However, it can only be used by qualified technical experts who have adequate knowledge and experience with nuclear energy technologies and systems and who are capable of taking into account all the factors associated with the specification of a roadmap. The experts should have access to all the information needed for constructing the roadmaps, including technical features and economic performance of the existing and future nuclear reactor and fuel cycle technologies, regulatory and support institutions and international cooperation mechanisms. Figure 18 shows the bottom-up structure of the roadmap template.

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[4] (a) Domination Identifier — an analytical tool for identifying non-dominated and dominated options from a set of considered feasible options; (b) Overall Score Spread Builder — an express tool for evaluating option overall score spreads caused by uncertainties in weighting factors and the objectives tree structure; (c) Rank Mapping Tool — a visualization tool for highlighting the first rank options for different combinations of high level objective weights; (d) Uncertainty Propagator — a traditional error-analysis-based tool for evaluating uncertainties in options' overall scores due to uncertainties in single-attribute value function forms and key indicators.

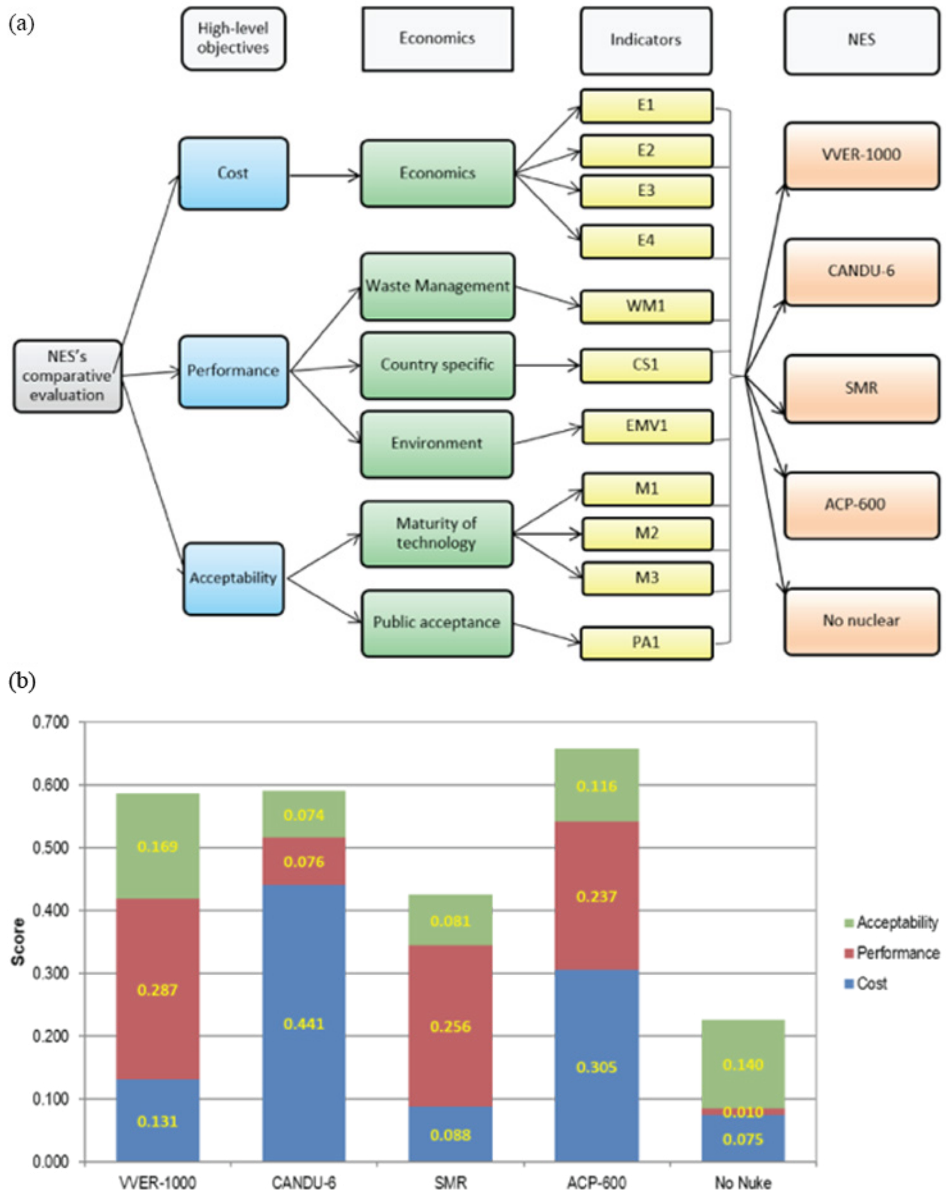

FIG. 16. (a) Objectives tree structure; (b) overall scores of alternatives for an Armenian case study.

ROADMAPS-ST includes 20 worksheets in a spreadsheet file, as shown in Fig. 19, for specifying various elements of a roadmap starting with: (a) a country profile characterizing the current status of the economy and energy of the country in question; (b) details of the nuclear energy sector, such as existing NPP and nuclear fuel cycle facilities as well as future plans for the development of nuclear energy in the long term; and (c) all the necessary data and information on nuclear energy technologies, possible collaboration arrangements and metrics and indicators for monitoring. The tool combines all these elements, following technical and practical logic, and supports experts and decision makers in developing an understanding of the main issues related to the transition to NESs with enhanced sustainability. It provides visualization of results with the help of Gantt charts, showing key events and developments on a timeline and an implementation schedule of action items for enhancing the sustainability of NESs. It includes nuclear fuel cycle material flow information for the existing and future reactor fleet and the associate front end and back end of the nuclear fuel cycle. It allows analysis of the adequacy of nuclear fuel cycle infrastructure and determines the supply–demand balance for nuclear fuel cycle products and

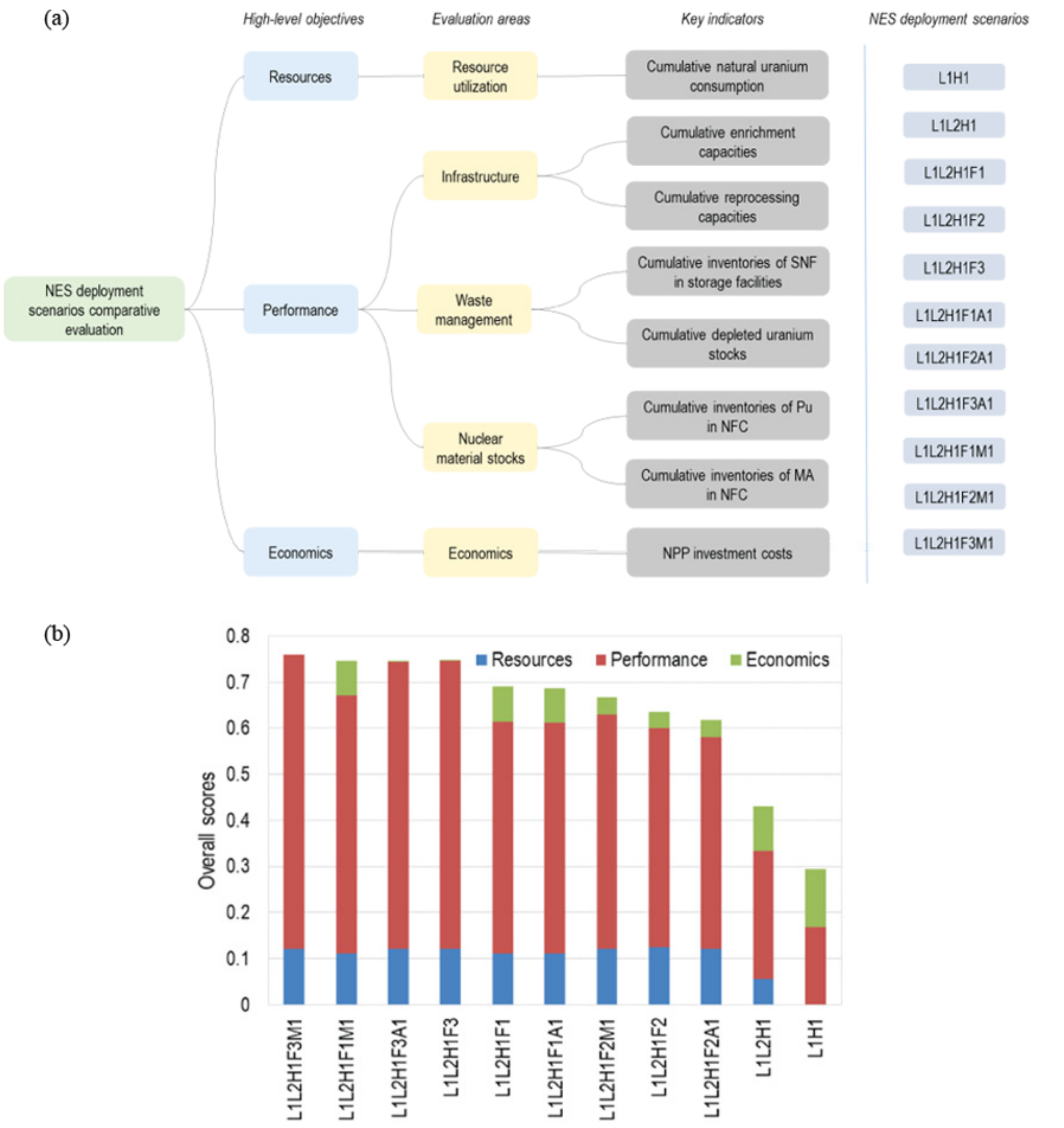

FIG. 17. (a) Objectives tree structure, and (b) overall scores of the NES deployment scenarios in a case study on the comparison of the GAINS scenarios.

services in relation to a given NES evolution over time. It can be linked with other tools for the calculation of material flow and acquiring data from publicly available national databases and informational sources.

To offer a clear and comprehensive image of the entire roadmap for the decision makers and stakeholders, a condensed form of the roadmap (see example in Fig. 20) is also prepared in the tool, highlighting the critical points.

The aggregation feature of ROADMAPS-ST allows the creation of regional and global roadmaps in a consistent manner and the identification of conflicting targets and goals in individual country level roadmaps. It can be modified, adapted and extended for a range of case studies focusing on strategic management and planning. It can be also used for reporting and preparing documentation for management, and for preparing public information on issues related to a transition to NESs with enhanced sustainability.

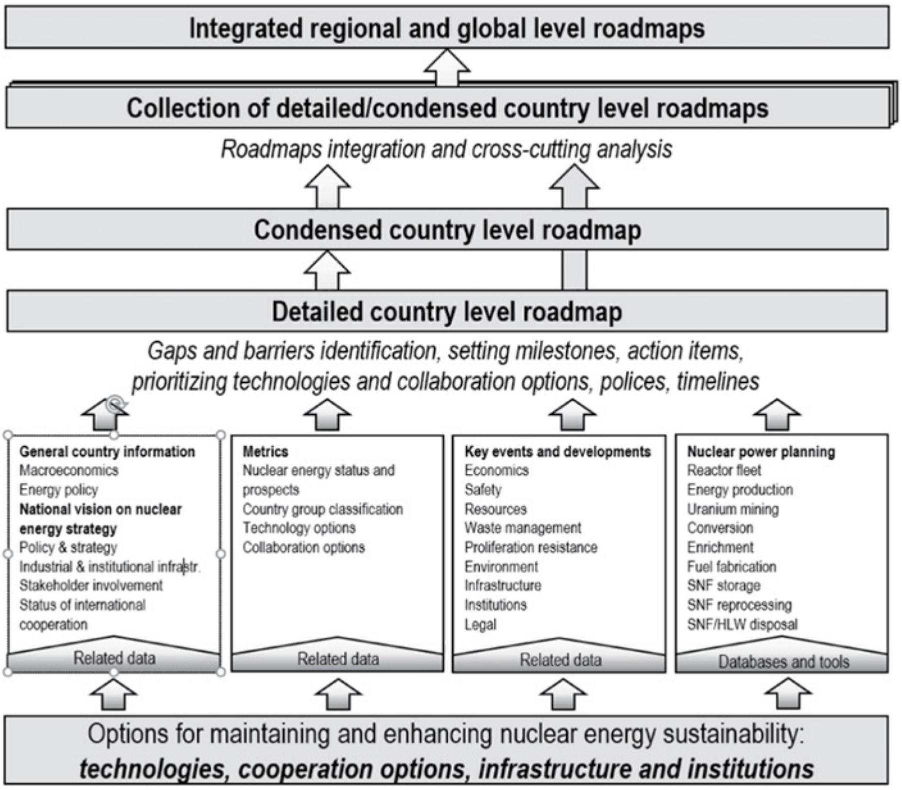

FIG. 18. Structure of the roadmap template. HLW — high level waste; SNF — spent nuclear fuel.

The evaluation of international and regional cooperation options in the roadmap template is very useful. Both commercial and cooperative schemes can be evaluated for enhancing the sustainability of global NESs.

The tool has been applied in several country case studies conducted under the ROADMAPS collaborative project, as well as for constructing roadmaps for the GAINS scenarios. Figure 20 shows a condensed roadmap for two GAINS scenarios — an NES based on a once-through nuclear fuel cycle with thermal reactors, and an NES based on a closed nuclear fuel cycle with thermal and fast reactors. In this example, the roadmap shows two options after 2035 for the reactor technologies: (i) continuation with thermal reactors and a once-through nuclear fuel cycle, or (ii) the introduction of a combination of thermal and fast reactors with a closed nuclear fuel cycle. These two alternative paths have to be compared in terms of sustainability criteria. Such a comparative evaluation can be performed using the KIND approach, which would identify the preference between the alternatives based on an overall ranking of the options.

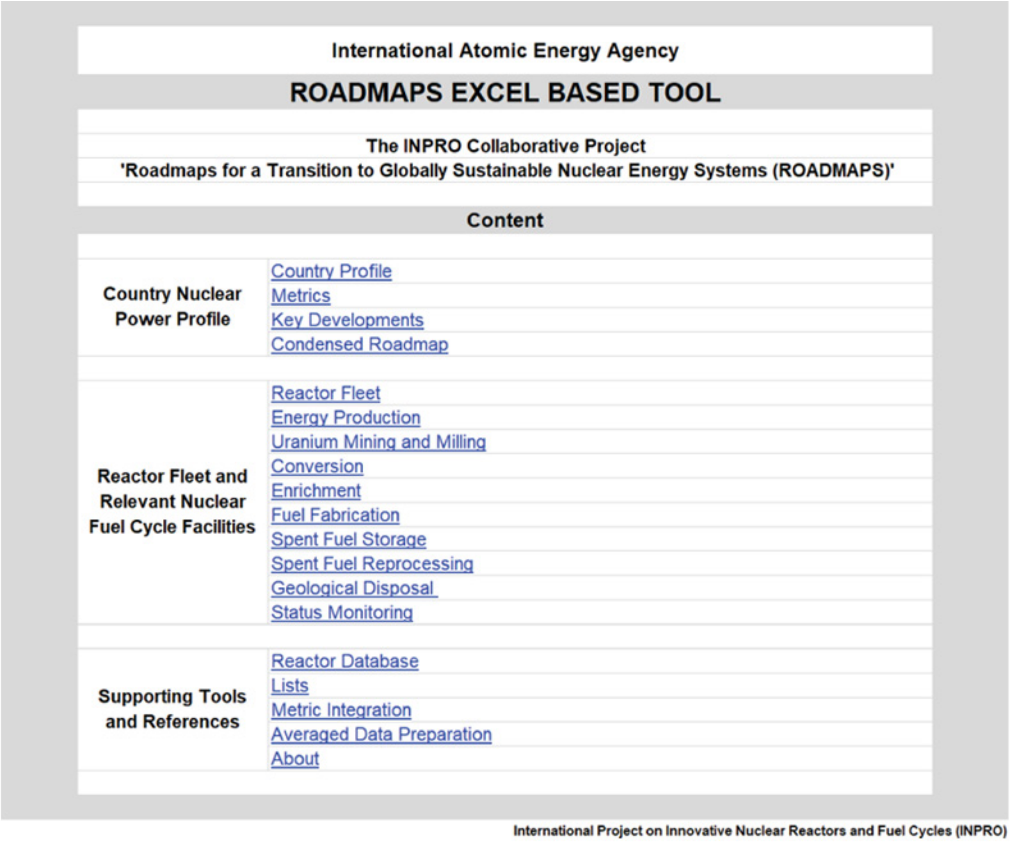

FIG. 19. Navigation panel of ROADMAPS-ST — the main worksheet.

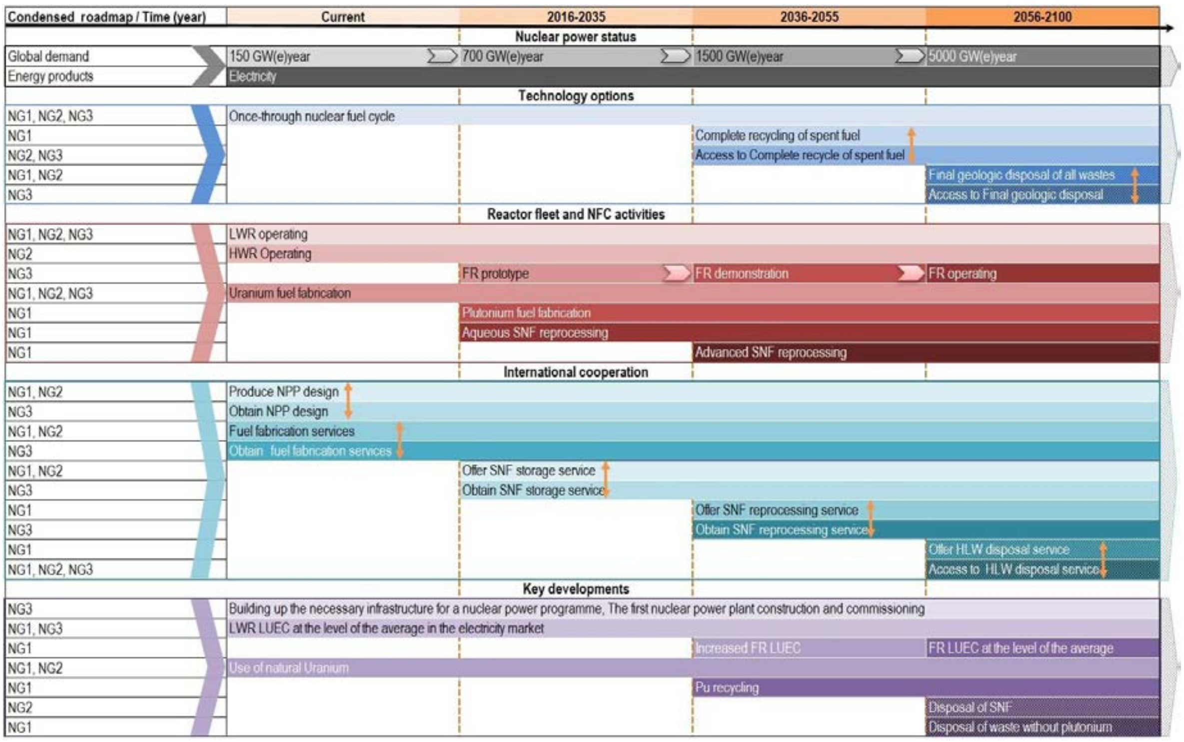

FIG. 20. Example of a condensed roadmap prepared for the GAINS scenarios.

5. SERVICE PACKAGE FOR MEMBER STATES: ANALYSIS SUPPORT FOR ENHANCED NUCLEAR ENERGY SUSTAINABILITY (ASENES)

5.1. PURPOSE OF THE SERVICE PACKAGE ‘ASENES’

The IAEA provides technical support to its Member States for the development of their nuclear energy programmes. This support encompasses the entire spectrum of activities necessary for the safe, secure and sustainable use of nuclear energy, ranging from strategic planning, infrastructure and human resource development, establishing and building institutions, framing legislation and regulations, technical evaluations, safety and security reviews, and so on. The various thematic areas require specialized technical support, including data, evaluation tools, guidance documents and the like, which are provided through a variety of services and activities.

In the case of strategic planning for nuclear energy, the basic objective is supporting informed decision making through the provision of up-to-date information on various nuclear energy technologies and appropriate analysis frameworks for formulating, comparing and road mapping alternative scenarios and strategies for the development of NESs with enhanced sustainability. The methodological approaches being offered are grounded on the knowledge base developed under INPRO since 2000. INPRO has already been providing support to interested Member States in the application of its assessment methodology, NESA.

One of the main tasks of INPRO has been the development of global and regional nuclear energy deployment scenarios to (a) provide a long term vision for the deployment of existing and innovative nuclear energy technologies, including fuel cycle facilities; (b) create understanding about the challenges for transition to NESs with enhanced sustainability; and (c) develop tools and metrics for the evaluation of alternative NES options and scenarios. The methodological approach for scenario development and analysis evolved under this task is equally applicable at the national level and has proven to be very helpful for exploring strategic directions for nuclear energy by both newcomer countries and countries with existing nuclear power programmes considering expansion [9, 10, 30]. The national level scenario and decision analyses provide a better understanding of the various options available to enhance the sustainability of nuclear energy at a country level aligned with possible developments at the regional and global levels.

Many Member States need technical support from the IAEA in using INPRO’s methodological approaches for developing nuclear energy deployment scenarios and conducting comprehensive studies for the formulation of and provision of a rationale for national strategies for sustainable NESs using relevant decision support tools. To meet this need, INPRO has developed the service package ASENES. The main purpose of this service is to provide technical assistance to interested Member States, including training and guidance on national strategic planning, decision making support and the long term development of nuclear energy programmes, taking into account the potential of technical innovation and possibilities for cooperation among countries. This service includes several elements that can be adjusted according to the specific needs of a country.

5.2. SCOPE AND ELEMENTS OF THE SERVICE PACKAGE ‘ASENES’

The scope of ASENES has been laid out to meet its objectives. It can cover the needs of a country that already has a nuclear energy programme and is contemplating gradual expansion (a technology user country). It can also cater to the needs of a technology holder country with a significantly large existing nuclear energy programme. It is, however, specifically suitable for a newcomer — a country

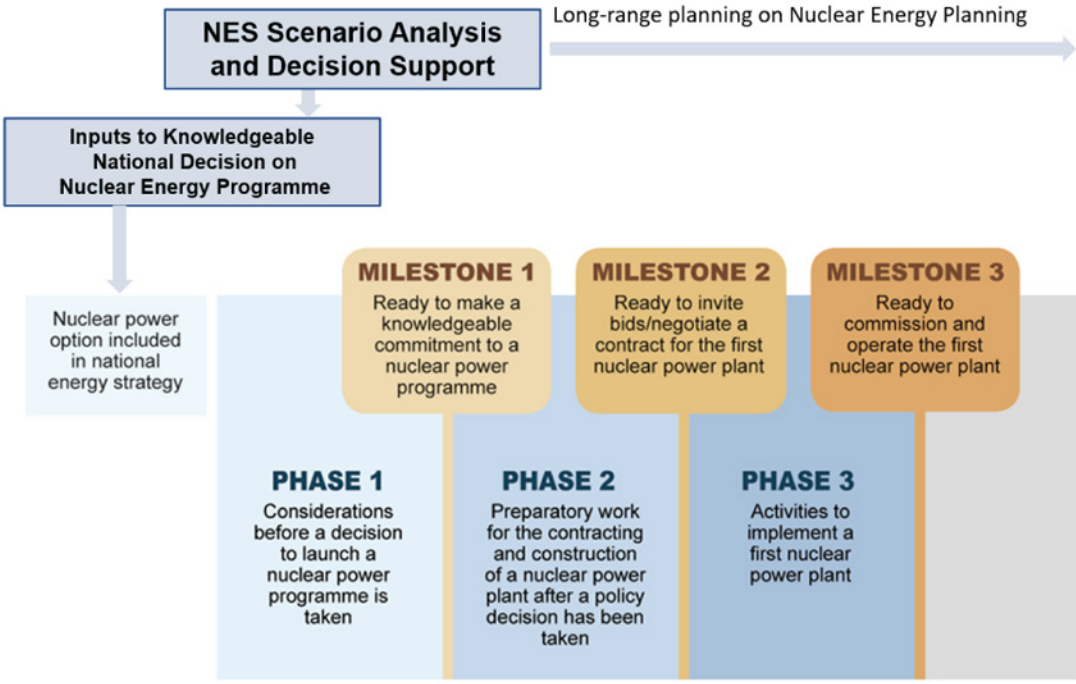

FIG. 21. Role of scenario analysis and decision support in national decision making for a newcomer country.

considering introducing nuclear energy to its future energy supply mix. Such a country would need to make a national decision based on a full understanding of the challenges and commitments over a long period and a thorough evaluation of nuclear energy's potential benefits for the country. INPRO support under this service would help develop the required understanding and would directly feed into the process of national decision making on the introduction of nuclear energy to a country, as shown in Fig. 21. This figure also shows the Integrated Nuclear Infrastructure Review service provided by the IAEA for establishing an adequate infrastructure for a national nuclear power programme [34].

In the case of a country with an existing nuclear energy programme, the service is very valuable in decision making on whether to expand the programme. Such a country would need to re-establish a need for nuclear energy and reaffirm the national position. In the case of an affirmative answer, the country would need to develop a strategy for the expansion of its nuclear energy programme, including a schedule of building future NPPs and fuel cycle facilities. The evaluation of possibilities for introducing innovative nuclear technologies and tapping into international, regional and bilateral collaboration opportunities would be an important feature of such a strategy. The INPRO service for NES scenario analysis and decision support can play a central role in this effort.

The ASENES service comprises several elements, as shown in Fig. 22:

— Capacity building activities aiming at strengthening local expertise for developing scenarios and decision making support for the safe, secure and sustainable development of nuclear energy;
— Technical guidance and tools for conducting national studies in exploring strategies and NES options and scenarios for the sustainable development of nuclear energy in the country;
— Exchange of experience through technical meetings to share experience in developing scenarios, decision support models and interpreting results.

Capacity building activities include: (a) training courses and workshops; (b) e-learning and distance training; and (c) on-the-job training for national experts and researchers for acquiring skills and knowledge.

INPRO regularly organizes training courses and workshops on NES scenario modelling and analysis at regional and international levels. These courses are conducted once per year and are targeted mainly

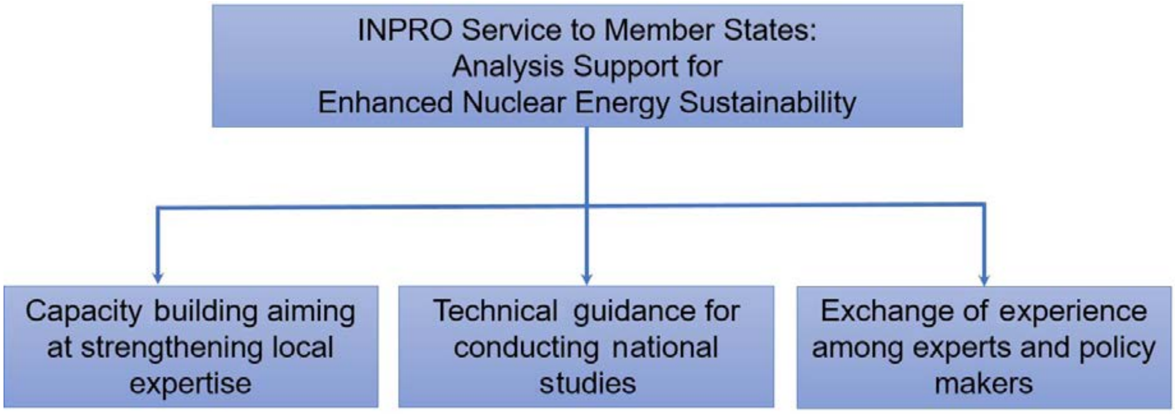

FIG. 22. Elements of the ASENES service package.

to participants from newcomer countries. The courses provide systematic training in developing models and scenarios on strategies for the sustainable development of an NES. Besides lectures and discussion sessions, the courses provide hands-on training in computer modelling, data analysis and scenario development. The participants, who are professionals in the field from Member States, are updated on technical and economic data on various nuclear technologies and acquire skills for using these data for developing models and scenarios. INPRO can also arrange, on request from interested Member States, such training workshops at the national level. The focus of these courses can be adjusted to the needs of Member States. Some generic training modules have been developed by INPRO for this service. A short description of these courses is given below.

(a) Training module on The Economics of Nuclear Power
This training module focuses on the economics of nuclear power and is based on the INPRO methodology for the economic assessment of NESs and the economic support tool NEST. This module includes overall information on the economics of nuclear power and the specifics of INPRO economic analysis and assessments supplemented by NEST. It includes details of a cost structure for a nuclear power project, the concept of the 'time value of money' (that funding available now is worth more than the same amount in the future because of its potential earning capacity), an approach to the calculation of the levelized unit electricity cost and some figures of merit for financial analysis. A variety of exercises is also included in applications of NEST for the evaluation of levelized unit electricity cost and its components, and the conduct of sensitivity analysis. The participants learn how to compute economic indicators that can be used for the evaluation of the cost competitiveness of different energy options and the attractiveness of investments.
(b) Training module on Nuclear Energy System Scenario Modelling and Analysis
This training module is intended to provide training in scenario modelling and analysis of NESs within the MESSAGE-NES framework. It focuses on defining the system boundaries and links to the outside world in a nuclear supply chain, and on the representation of various facilities in an NES with sufficient technical and economic details. This module also includes guidance on input data preparation and the development of alternative scenarios. Another component in this module is the analysis and interpretation of scenario results to understand key issues for transition to future sustainable NESs. The training is imparted through specialized lectures, exercises and hands-on work sessions. The participants develop their skills in modelling NES deployment and performing scenario analysis, including developing alternative scenarios.
(c) Training module on Comparison and Ranking of Nuclear Energy System Options and Scenarios
This training module focuses on the comparative evaluations of NES options and scenarios and is based on the KIND approach and KIND-ET tool. The participants are trained in the use of KIND-ET for country studies. Lecture topics include concepts and methodologies for comparative evaluation

in a multicriteria situation. Training is given in all the steps of the structured comparative evaluation approach, starting with problem formulation and the identification of indicators, to the application of KIND-ET for the comparative evaluation of NES options and scenarios and the analysis of results. The module includes exercises on the application of multicriteria decision analysis for the comparison of alternatives and dealing with uncertainties. The participants learn how to perform comparative evaluations of NES options and scenarios that can be used for supporting the selection of the most preferred alternative for an NES with enhanced sustainability.

(d) Training module on Road Mapping towards Nuclear Energy Systems with Enhanced Sustainability
This training module aims at providing training to Member States in developing country roadmaps for progressive transition to NESs with enhanced sustainability. The participants collect and compile information for analysing the gaps, key events and developments, status, prospects, benefits and risks associated with a variety of options for NES deployment. They are trained in representing alternative scenarios using the roadmap template and ROADMAPS-ST to identify opportunities for saving time, efforts and resources for improving the characteristics of a national NES through the introduction of innovative technologies and international cooperation.

Face-to-face training courses and workshops are supplemented with e-learning and distance training.[5] These sessions help prepare, in advance, the participants to attend the regular training courses. The participants are introduced to recent developments in nuclear reactor and fuel cycle technologies, the conceptual basis for strategic planning, modelling of NES development scenarios and the methodological approaches for scenario analysis and decision support for NESs with enhanced sustainability. The objective is to enhance the effectiveness of the regular training. E-learning and distance training sessions also help economize the cost and effort for imparting the regular training.

Training without a follow-up is of limited effectiveness. INPRO, therefore, works closely with interested Member States and offers on-the-job training opportunities. National experts can avail themselves of opportunities to work with INPRO staff, under various arrangements, and acquire experience in NES modelling, scenario analysis and decision support through participating in ongoing INPRO studies, and in the process develop expertise that would prepare them to effectively feed systematically analysed information to the national decision making of their country. This practical way of learning also deepens the understanding of theoretical concepts and enables national experts to be more creative in exploring alternatives for the development of NESs with enhanced sustainability (Table 2).

Another element of the service package ASENES is technical guidance. INPRO offers, on request from Member States, technical support in the conduct of national studies for exploring alternative strategies for the development of nuclear energy with enhanced sustainability. The provision of guidance can be tailored to the needs of the national team. It can include expert advice on designing the national study, the collection of data, constructing national NES models, developing NES deployment scenarios and decision support models, and analysing results. Such technical guidance is spread over a multiyear period during which the national team develops a close working relationship with the INPRO experts and benefits from their experiences. Peer review of the national scenarios, data, tools, models, analyses and results can also be arranged.

Yet another important element of the service package is organizing technical meetings for the exchange of experience. These meetings are intended to share experience in developing scenarios, decision support for transition to an NES with enhanced sustainability and analysing models and results. The participants enrich their understanding by interacting with professionals from other countries and by sharing information and experiences with one another. Such meetings can also open up opportunities for collaboration among the professionals involved and establish informal and formal networks. In addition to the researchers and technical experts, senior planners and policy makers are welcome to attend these meetings.

[5] In periods when it was not possible to deliver in-person courses owing to travel and movement restrictions, equivalent courses have been delivered on-line.

5.3. USERS OF THE SERVICE PACKAGE ‘ASENES’

The service package ASENES is targeted to all Member States, including technology holder countries, technology user countries and newcomers. More specifically, the planning departments in these Member States, which are entrusted with the responsibility of the development of nuclear energy programmes, can be the main users of the service, for example, the planning department in the atomic energy commission or department of atomic energy, or similar governmental bodies in a country. These governmental institutions can select and choose from the various elements of this service package according to their specific needs.

Among the technology users, those Member States just considering nuclear energy as a possible option for meeting their future energy needs can select the elements from the service package that focus on scenario analysis for comparing nuclear and other energy technologies and combine technical, economic and environmental aspects in the evaluation of various technological options.

Member States that have determined that nuclear energy is a suitable option for meeting their future energy needs and intend to embark on introducing a nuclear energy programme can select several elements of the service package ASENES they would need to assess the long term consequences — costs, benefits, risks and so on — of the alternative technological options and develop strategic plans and roadmaps for progressively developing their NES.

The service package ASENES is also very useful for Member States that are already using nuclear power and are considering expanding their nuclear energy programmes. These countries can utilize elements from the service package that are intended to enrich the experience of planning and assessing the sustainability of NESs, and also to develop support for decision making.

The service package can also be used by Member States that have made a decision not to pursue nuclear energy but may consider revisiting that decision or initiating a national dialogue on it. Such countries would need to conduct national studies to evaluate the nuclear energy option under potentially emerging conditions and assess the long term consequences for the country.

Member States that are characterized as technology developers, or those that intend to become technology developers in the future, can use the service for assessing potential markets for their nuclear energy technologies. These countries can also use the INPRO methodological approaches to scenario

TABLE 2. CAPACITY BUILDING FOR SCENARIO ANALYSIS AND DECISION SUPPORT FOR THE DEVELOPMENT OF NESs WITH ENHANCED SUSTAINABILITY

Element	Purpose	Delivery mechanism
Training courses and workshops	Provide training on the use of INPRO tools for the comprehensive evaluation of NES options and scenarios	• Regional courses and workshops; • On request national courses and workshops; • Regional and national technical cooperation projects.
E-learning and distance training	Introduce INPRO approaches and tools for the comprehensive evaluation of NES options and scenarios and provide initial training for their use	• INPRO distance training courses through available distant communication applications; • On request national training through available distant communication applications; • As part of a pre-training session of a training course.
On-the-job training	Deepen understanding of INPRO approaches and tools for the comprehensive evaluation of NES options and scenarios and improve skills to apply them for the comprehensive evaluation of NES strategies and scenarios for enhanced sustainability	• Fellowship under national technical cooperation projects; • Cost free experts; • INPRO initiatives under collaborative projects.

analysis and decision support for identifying priority areas for innovations and R&D in nuclear technologies according to national, regional and global needs, and for exploring pathways for a transition from presently available nuclear reactors and fuel cycle technologies to NESs with enhanced sustainability.

This service package also targets the research institutions engaged in the conduct of national studies for supporting the formulation of long term plans and strategies for the development of nuclear energy programmes. The research teams can utilize the analytical tools and methodological approaches for designing more imaginative and futuristic scenarios and exploring the possibilities for a long term future.

Interested Member States can request the service through appropriate official channels. The annex details the procedures for requesting the service and accepting the request by INPRO. The request form for the INPRO ASENES service is also included in the annex.

5.4. BENEFITS TO MEMBER STATES

The objective of ASENES is to develop global and regional nuclear energy scenarios, using scientific and technical analysis tools that have been developed, that lead to a global vision of sustainable nuclear energy development in the current century and beyond.

Based on this objective the benefits for Member States are that:

- It would strengthen their nuclear energy institutions by building local expertise in the analysis and evaluation of various options for nuclear energy development, developing decision making support and assessing, in a systematic way, the sustainability of their nuclear energy programmes. Without competent professionals, the challenging task of analysing complex interlinkages of the technical, economic and environmental aspects of nuclear energy technologies cannot be performed adequately. Through the capacity building activities of this service, interested Member States can obtain training for their professionals in the use of appropriate tools developed by INPRO for scenario analysis, decision support and strategic planning for NES deployment. Member State experts can enhance their skills in data analysis, the modelling of NESs, developing NES options and scenarios, the analysis of results and the multifaceted evaluation of alternatives. Equipped with analysis tools and competence in systematic analysis, Member State experts will be able to contribute more effectively to national decisions on the planning and development of nuclear energy in the country.
- Interested Member States can also benefit from the technical support and guidance offered under this service for the conduct of national studies for developing scenarios and evaluating the sustainability of alternative NESs. Such national studies, carried out under the auspices of INPRO, would help Member States chart their national strategies for the development of NESs with enhanced sustainability.
- The national institutions responsible for the planning and development of nuclear energy would be able to establish systematic planning processes that would ensure the selection of technological options that are compatible with enhancing the sustainability of NESs. The service would be helpful to create a better understanding of the nuclear role in the long term sustainability of energy production according to national priorities in the mitigation of its influence on the environment, the security of supply, the safety of electricity production, and international collaboration on the economic attractiveness of the nuclear fuel cycle.
- Through facilitation of the exchange of experience under this service, senior policy makers and planners in Member States would be able to better appreciate the value of scenario and decision analyses for the strategic planning of nuclear energy development and understand the possible long term consequences of technological choices for nuclear reactor systems and their corresponding fuel cycles. The sharing of experience would also help create opportunities for cooperation and collaboration among Member States in strategic planning for nuclear energy development.

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ABBREVIATIONS

ASENES	Analysis Support for Enhanced Nuclear Energy Sustainability (IAEA INPRO project service package)
GAINS	INPRO Collaborative Project Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (IAEA project within INPRO)
HWR	heavy water reactor
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles (IAEA project)
KIND	Key Indicators for Innovative Nuclear Energy Systems (IAEA project within INPRO)
MESSAGE	Model for Energy Supply System Alternatives and their General Environmental Impacts (IAEA code)
MOX	mixed oxide fuel
NES	nuclear energy system
NEST	Nuclear Economics Support Tool (IAEA project within INPRO)
NESA	Nuclear Energy System Assessment (IAEA project within INPRO)
NPP	nuclear power plant
R&D	research and development
ROADMAPS	for a Transition to Globally Sustainable Nuclear Energy Systems (IAEA project within INPRO)
SDG	Sustainable Development Goal
SYNERGIES	Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (IAEA project within INPRO)

Annex

GUIDELINES FOR REQUESTING THE SERVICE PACKAGE ANALYSIS SUPPORT FOR ENHANCED NUCLEAR ENERGY SUSTAINABILITY (ASENES)

A–1. INTRODUCTION

The IAEA offers technical support to its Member States in all aspects of their nuclear energy programmes. This support encompasses the provision of technical information, guidance, peer reviews and direct support for strengthening local expertise and skills, as well as for establishing national nuclear institutions for ensuring the safe, secure and economic use of nuclear energy. Several programmes and services have been established not only for supporting technical aspects but also for the planning and managing of nuclear energy development.

To support interested Member States for formulating national strategies for the development of their nuclear energy systems with enhanced sustainability, the IAEA, within INPRO, has developed a service package entitled Analysis Support for Enhanced Nuclear Energy Sustainability (ASENES). The main purpose of this service is to provide technical assistance, including training and guidance, for conducting comprehensive studies on long term nuclear energy scenarios and supporting decision making for strategic planning of nuclear energy programmes, taking into account the potential of technical innovations and possibilities for cooperation among countries.

This annex outlines the principles and procedures for requesting and providing INPRO support under this service.

A–2. PRINCIPLES AND PROCEDURE FOR PROVIDING INPRO SUPPORT

The IAEA supports its Member States in their national efforts towards sustainable development through the provision of technical support for building human and institutional capabilities, transferring nuclear technologies and disseminating knowledge and technical information. The IAEA's support is guided by the decisions of its governing bodies, its Medium Term Strategy[1] and Member States' needs communicated through various meetings. It covers a host of key areas for sustainable development, ranging from agriculture to health, water, energy, the environment and so on.

As nuclear energy has a sizeable potential for providing sustainable energy supplies, the IAEA provides a wide range of technical support for ensuring the safe, secure and economic use of nuclear energy that covers the entire spectrum of activities.

For strategic planning for nuclear energy, through INPRO the IAEA supports interested Member States in their long term planning for deploying sustainable nuclear energy systems. It provides direct support related to advanced and innovative nuclear energy system scenario modelling and analysis, decision support analysis and sustainability assessment using the INPRO methodology and through facilitating dialogue, cooperation and collaboration among Member States in their respective roles as nuclear energy technology developers, suppliers and technology users.

As INPRO is a membership based project, the INPRO Steering Committee, comprising representatives of INPRO members, directly guides its programmes and activities. The steering committee meets regularly to review progress, define priorities and provide guidance on future activities. In its recent meeting, the steering committee recommended that INPRO include in its programme a new service for Member States related to INPRO Task 1 'Global scenarios'. Responding to this recommendation, INPRO has launched a new service to Member States, ASENES.

[1] Medium Term Strategy 2018–2023, Resolution GOV/2016/57, IAEA, Vienna (2016).

This service is available to all Member States that have determined that nuclear energy is a suitable option for meeting their future energy needs and (a) intend to embark on introducing a nuclear energy programme, or (b) are already using nuclear power and are considering expanding their nuclear energy programmes. The service is also available for technology developers for evaluating the future market potential for their nuclear energy technologies or identifying priority areas for innovation and R&D in nuclear technologies.

INPRO will provide this service on official request from a Member State with an assured commitment of allocating necessary resources to the proposed project. The details and scope of the INPRO service can be adjusted according to the needs of each Member State.

A–3. ROLES AND RESPONSIBILITIES

The Member State will have ownership of the proposed project and will assume full responsibility for it. It will identify one or more suitable counterpart institutions and other stakeholders and will establish a project team.

In consultation with the INPRO team, the project objectives, scope and work plan will be defined by the designated counterpart institution(s) with contributions from other stakeholders in the country.

The lead counterpart will plan and coordinate the project activities and ensure the timely completion of all tasks while achieving a high technical quality.

The lead counterpart and the project team members should have adequate professional competence, knowledge and experience.

The INPRO team will work closely with the project team and provide technical support within the scope of ASENES. The inputs from INPRO — the transfer of analytical tools, training of project staff, guidance for conduct of studies and so on, will be cost free. Member States will bear all local costs and, in some cases, will share a part of the INPRO cost.

A–4. INPRO SERVICES

The INPRO ASENES service package includes (a) training; (b) the transfer of analytical tools; and (c) guidance on the conduct of studies. Table A–1 below shows the main components of the service package. In each case, the details of INPRO support will be adjusted according to the specific needs of the country.

A Member State can request only a national training event or it can request a review of its study or comprehensive support for a project aimed at conducting a detailed study, guided by INPRO, on nuclear energy scenarios for developing long term strategies for a sustainable nuclear energy programme. In such a case, a project may include the following inputs from INPRO:

(a) Training of the project team:
   (i) E-learning and distance training;
   (ii) Hands-on training in the use of INPRO tools for the evaluation of nuclear energy system (NES) options and scenarios;
   (iii) On-the-job training to strengthen skills for scenario analysis, comparative evaluation and road mapping of NES options and scenarios for enhanced sustainability.
(b) Guidance for the conduct of scenarios and the decision analysis study:
   (i) Expert support for constructing the NES and decision support models and for data preparation;
   (ii) Expert support for scenario analysis and decision support;
   (iii) Peer review of analyses and results.

TABLE A–1. INPRO SERVICE

Element	Purpose
Training courses and workshops	Providing hands-on training on the use of INPRO tools for the evaluation of NES options and scenarios
E-learning and distance training	Introducing INPRO approaches and tools for the evaluation of NES options and scenarios
On-the-job training	Deepening understanding of INPRO approaches and tools for evaluation of NES options and scenarios and improving skills to apply them for the comprehensive evaluation of NES strategies and scenarios for enhanced sustainability
Technical guidance	Providing guidance for the conduct of national studies for exploring alternative options and scenarios for the development of a sustainable NES, including expert advice on constructing a national NES and decision support models, the collection of data, developing scenarios and analysing results
Exchange of experience	Sharing experience on developing and analysing scenarios, decision support models and results for improving understanding through interaction among professionals from different countries

REQUEST FORM FOR INPRO SUPPORT FOR A NATIONAL PROJECT

ANALYSIS SUPPORT FOR ENHANCED NUCLEAR ENERGY SUSTAINABILITY

Country name	
Project title	
Project duration	
Counterpart institution(s)	
Names and contact details of project counterpart(s)	
Project summary	

SECTION 1: PROJECT BACKGROUND AND JUSTIFICATION

Background and justification of the project	Describe the national energy situation and future plans for providing sustainable energy supplies, including the potential contribution from nuclear energy. Provide a review of past efforts and studies on energy and nuclear power planning, including those supported by the IAEA, if any. Give a justification for the current project.
Partners and stakeholders	Describe the relevant stakeholders, end users, beneficiaries and partners and their roles and responsibilities in the project.
Overall objective of the project	Describe the overall objective of the project and its linkage to the national development programme and long term energy plan.

SECTION 2: PROJECT DESCRIPTION

Specific objectives of the project	Describe the specific objectives of the project, and what benefits would be achieved using the project outputs.
Performance indicator(s)	Describe what indicators will be used to measure performance. Indicators should be SMART (specific, measurable, achievable, realistic, timely).
Project outputs	Describe what tangible and intangible outputs the project will produce.
National resources available for the project	What national resources — infrastructure, human and financial — are (or will be) available to implement the project at the counterpart institution(s)?
IAEA/INPRO support requested	Describe what IAEA/INPRO support is needed for achieving the project objectives and producing the planned outputs.
Implementation approach	Describe what implementation approach will be used and which steps will be taken to achieve the project objectives and produce the outputs. Describe what roles are expected from the participating institutions and other stakeholders. State how the project ownership and the commitment of resources will be ensured.
Project work plan	Describe in detail the work plan for the project, elaborating: — The main milestones; — All the activities to be implemented; — The timeline or schedules for producing planned outputs; — The review process.
Progress monitoring and review	Describe how the progress will be monitored, and how any corrective actions would be taken, if needed.

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Technical Meetings

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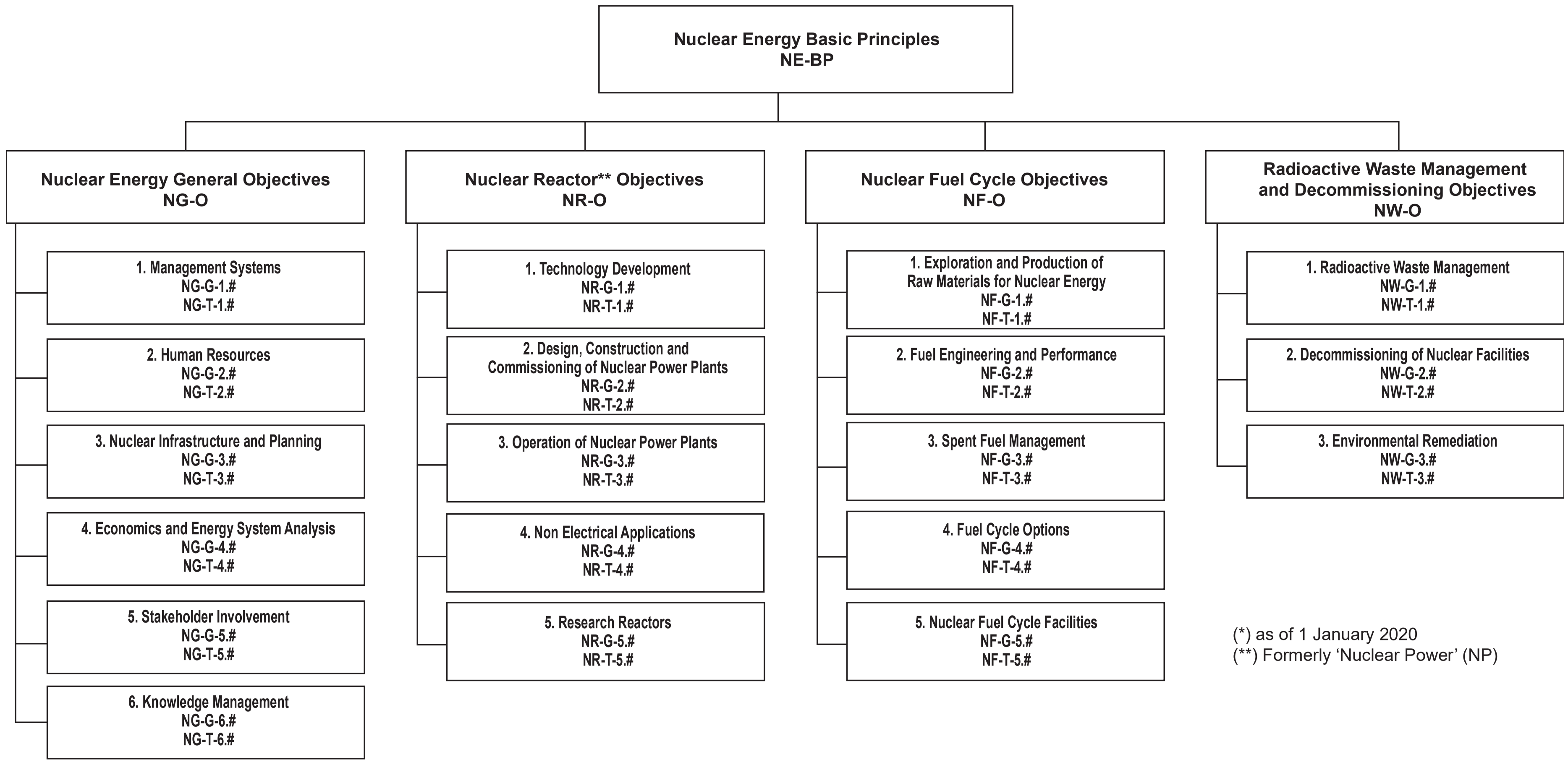
Structure of the IAEA Nuclear Energy Series*



(*) as of 1 January 2020
(**) Formerly 'Nuclear Power' (NP)

Key

BP: Basic Principles
O: Objectives
G: Guides and Methodologies
T: Technical Reports
Nos 1–6: Topic designations
#: Guide or Report number

Examples

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NR-T-5.4: Nuclear Reactors (**NR**)*, Technical Report (**T**), Research Reactors (topic **5**), **#4**
NF-T-3.6: Nuclear Fuel (**NF**), Technical Report (**T**), Spent Fuel Management (topic **3**), **#6**
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