IAEA NUCLEAR ENERGY SERIES No. XXXXX

MODEL CURRICULUM ON STRATEGIC PLANNING FOR SUSTAINABLE NUCLEAR ENERGY

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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 2000, based on the resolution of the IAEA General Conference (GC(44)/RES/21), to help ensure that nuclear energy remains available to contribute to meeting global energy needs until the end of the 21st century. The INPRO is a membership-based project, guided by its Steering Committee composed of representatives from the member countries and the European Commission (EC). It supports its members with their long-term planning and collaboration on innovations in reactors, fuel cycles and institutional approaches promoting the sustainable development of nuclear energy. INPRO's activities are centred on the key concepts of global nuclear energy sustainability and the development of long-range nuclear energy strategies, so that nuclear energy can contribute in a sustainable manner to the global energy needs for the current century and beyond.

To assist members in assessing the long-term sustainability of nuclear energy systems, INPRO developed a set of basic principles, user requirements and criteria, and an assessment method which together comprise the INPRO methodology for the evaluation of the long-term sustainability of nuclear energy systems (NES). The INPRO methodology covers all areas relevant to NES sustainability, reactor types and fuel cycle facilities, all facilities of an NES, and all phases of an NES from the cradle to the grave. Furthermore, INPRO has developed a framework for analysing and assessing transition scenarios to sustainable nuclear energy systems. The scenario analysis and decision support frameworks, together with the INPRO methodology and evaluation tools, have proven to be extremely useful for weighing the possible national choices for the scope and extent of national nuclear energy programmes and the needed collaboration with other countries for sustainable nuclear energy development.

The IAEA General Conference 65 in its Resolution GC(65)/11 emphasized the important role that the Agency can play in assisting interested Member States in building long-term national nuclear energy strategies based on the INPRO methodology. And requested the Secretariat, inter alia, to assist Member States in their efforts to ensure the sustainability of nuclear education and training in all areas of the peaceful use of nuclear energy. In this respect, INPRO has initiated an effort to develop a model curriculum for introducing courses/modules on strategic planning for sustainable nuclear energy development. These courses/modules can be adapted by the universities in interested Member States respecting their academic autonomy and the national accreditation system in place and be offered in their regular master's degree programmes. The INPRO Steering Committee also recognized the need for building the foundations for required competence for developing long term strategies for sustainable nuclear energy development that can be met through introducing necessary educational programmes at the university level.

This publication is intended to provide a model curriculum for a master’s degree course covering topics related to the strategic planning for sustainable nuclear energy development. The publication can be used by developers of university curriculum developers as well as faculty and instructors from academic and other educational institutions, including centres of excellence and vocational education, that are implementing or considering educational programmes on the long-term planning for sustainable nuclear energy development.

The IAEA officer responsible for this publication was M. Gladyshev of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The world community recognized that present patterns of consumption and production are unsustainable and must change significantly [1]. The planet cannot sustain the current depletion of resources, environmental degradation, and other stresses on the eco-systems. To achieve a sustainable future the United Nations identified seventeen Sustainable Development Goals (SDGs) [2], which all United Nations Member States adopted in 2015. The UN defined sustainable development as development "that meets the needs of the present without compromising the ability of future generations to meet their own needs" [3]. The concept of sustainable development reaches across all sectors of the economy. The overriding core message is that while meeting needs of the current generation, excessive burdens, such as climate change, natural resource exhaustion, and undisposed hazardous wastes, should not be left that compromise the well-being of future generations.

Energy is critical for all social and economic activities and plays a central role in sustainable development. The key challenge for sustainable energy development is to address the interactions among the four dimensions: economic, environment, social, and institutional, in a balanced way[1], and making relevant trade-offs. Nuclear energy has the potential to make a significant contribution to sustainable energy.

The present global energy system relies heavily on fossil fuels, which are not only finite and depletable but also cause substantial environmental damage. Fossil fuels are considered to be the main source of greenhouse gas emissions (GHGs) causing climate change. Consequently, the present energy system is not compatible with sustainable development. Nonetheless, a range of energy technologies can support the UN Sustainable Development Goals, particularly SDG7: Affordable and Clean Energy. Nuclear energy is one of the technology options that offers reliable, economic and clean electricity generation. Nuclear power is in fact already making an important contribution to sustainable development by providing over 10% of the world electricity generation at competitive costs while avoiding approximately 2 billion tons of CO2eq emission annually [4]. Nuclear energy directly supports the realization of sustainable development goals for Energy (SDG7) and Climate Action (SDG13).

Currently there are about 440 nuclear reactors in operation, and more than 50 reactors under construction[2]. This represents a nearly 12% growth to the deployment of nuclear reactors. The new reactors are, for the most part, large light water-cooled reactors of the Generation-III and Generation-III+ designs. However, results of the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) collaborative projects[3] showed that nuclear energy sustainability requires major innovations in nuclear reactor and fuel cycle technologies, as well as institutional innovation.

New nuclear reactors, nuclear fuels and associated technologies are under development and demonstration worldwide. Cooperation among countries in the creation of optimized nuclear fuel cycles systems is essential for sustainable development.

For any country considering the use or expansion of nuclear energy a number of key evaluations are necessary for making responsible decisions. There are both near-term issues and longer-term considerations associated with the use of nuclear energy, which may span 100 years or more. The key areas for evaluation include the environment, safety, proliferation

[1] The concept of the four dimensions of sustainable development is in Annex I

[2] IAEA PRIS database as of September 2022

[3] Collaborative Projects are an important part of INPRO's activities proposed by and carried out with active participation of INPRO members

resistance, waste management, infrastructure, and economics**.** The INPRO Methodology supports a sustainability assessment of a nuclear energy system (NES) in these six key areas.

Additionally, INPRO developed a set of technical and comprehensive scenario analysis and decision support tools for developing nuclear energy scenarios and conducting studies for formulating national strategies for sustainable nuclear energy systems. The INPRO tools can be helpful for all Member States, who have identified that nuclear energy is a suitable option for meeting their future energy needs and intend to embark on introducing nuclear energy programme or are already using nuclear power and are considering expanding their nuclear energy programmes.

The rationale for developing a master's level model curriculum on nuclear energy strategic planning using the IAEA INPRO methods and approaches is to prepare graduates from university programmes to gain an awareness and understanding of the INPRO methodology and capabilities. This will allow countries and organizations to make the best-informed decisions on the future use of nuclear energy systems. The introduction of the courses based on the model curriculum in the educational process will contribute to the expansion and deepening of knowledge about the long-term sustainability aspects of nuclear energy systems. It is essential that information on INPRO activities be delivered to young professionals, lecturers and students at technical universities and other relevant educational organizations, who will further be engaged in development and deployment of sustainable solutions for nuclear systems in the IAEA Member States.

1.2. OBJECTIVES

The intention of this publication is to provide a model curriculum for a master's degree course in strategic planning for sustainable nuclear energy development. The publication is useful for university curriculum developers (including faculty and instructors from academic and other educational institutions, centres of excellence and vocational education institutes,) that are responsible for implementing educational programmes on the long-term planning of sustainable nuclear energy.

1.3. SCOPE

A number of universities offer high quality programmes in the field of nuclear science and engineering. These programmes cover the basics of nuclear engineering, including key areas such as reactor technology and nuclear energy systems, reactor physics, thermal hydraulics, reactor safety, nuclear fuel cycles, materials for nuclear applications, radiation environments, computation and simulation, radiological health engineering, radiation protection, medical physics, plasmas, and fusion. These programmes provide strong coverage of the technical disciplines in the nuclear energy field. However, for countries to utilize nuclear energy there are several other areas, such as economics, infrastructure, waste management and others, that programmes in the field of nuclear science and engineering should address. The INPRO developed methodology and tools to address these needs.

This publication offers a framework for a master's degree course in strategic planning for sustainable nuclear energy development. The scope of this publication covers the following topics.

— Planning and strategies for sustainable energy development

— Planning for nuclear energy sustainability

— Technological and institutional innovations in nuclear energy sector in meeting sustainable energy development challenges

- Introduction to IAEA INPRO methodology for assessing sustainability of nuclear energy systems
- Introduction to methods and tools for sustainable energy development
- Methods and tools for modelling and analysis of nuclear energy systems
- Research projects on planning and assessment of overall energy systems and, in particular, nuclear energy systems.

1.4. TARGET USERS

This publication is for individuals with responsibility for developing and delivering programmes to educate specialists in the nuclear field and in other fields associated with strategic planning for sustainable nuclear energy development. These individuals may be academic leaders in universities, as well as policy and decision makers at the governmental level, in responsible ministries and agencies dealing with energy, science and/or education. The users of this publication may come from universities, centres of excellence or vocational institutions in embarking countries that are anticipating the use of nuclear energy, and universities in countries having already nuclear energy programmes and assessing their existing capabilities or considering an expansion of the nuclear role.

1.5. STRUCTURE

The following is an overview of the sections in this publication.

Section 1 provides the background and objectives of this publication. It explains the rationale for developing a model curriculum on strategic planning for nuclear energy development, based on the IAEA INPRO methodology and approach.

Section 2 provides the purpose of the course and general expectations. It explains how the curriculum and corresponding courses can be incorporated into university academic programmes. This section also addresses the intended audience for the course and prerequisites for the course participants.

Section 3 covers the methodology for the development of curriculum and identifies the competency areas addressed in the curriculum. This section covers the structure of the curriculum along with suggested modules. The curriculum has three parts: core modules, advanced modules, and a research project module.

Section 4 analyses of IAEA support for implementation of the model curriculum. The section presents the IAEA analytical tools for overall energy planning and for nuclear energy system modelling and analysis. Additionally, this section gives procedure and mechanism for obtaining the IAEA tools including training.

Appendix I provides a detailed description of the curriculum modules and elaborates the learning objectives, prerequisites for the study, learning outcomes, module topics, and suggested teaching delivery methods and student performance assessment, for each of the module.

Appendix II presents a short description of the IAEA energy planning tools and the INPRO analytical tools for evaluating alternative nuclear energy systems.

An Annex that describes the concept of sustainable development and its relationship with the INPRO methods and approaches.

2. PURPOSE OF AND PREREQUISITS FOR THE COURSE

2.1. PURPOSE OF THE COURSE AND GENERAL EXPECTATIONS

The model curriculum along with associated educational modules presented in this document is for universities and can be incorporated into academic programmes. It is generally anticipated that the curriculum will be used as part of master's programmes in nuclear engineering and other fields associated with strategic planning for sustainable nuclear energy development. The material is sufficiently broad that it can be also of interest to students in disciplines such as engineering, physics, energy economics, planning and policy. The proposed curriculum can be used by universities in several ways. This can be adapted as a single course, however, the material in the model curriculum is very comprehensive and, therefore, can be utilized for several courses. As an additional alternative, universities could utilize this model curriculum as a basis to create an entire master's programme. The decision on how to proceed with the model curriculum and the associated material is up to implementing university. The IAEA can support interested universities to determine how best to implement the model curriculum in their educational programme.

The courses[4] that can be based on the suggested modules have several objectives. These include:

- Provide an update on the current status of electricity generation in the world; with emphasis on pros and cons of all possible energy sources including nuclear energy as well as renewables.
- Provide an independent overview of the current status and future developments in the nuclear energy industry around the world, including existing and advanced power-reactors, including small modular reactors (SMR) designs, and Generation-IV reactor concepts, and other advanced concepts.
- Deliver a description of the evaluation capabilities of the INPRO approaches and tools for application to nuclear energy systems based on different types of nuclear power plants and their fuel cycles.

The course modules are structured with sufficient breadth and depth to enable students to use INPRO methods and approaches, and provide context and guidance for exploring nuclear energy strategic planning. The modules form the basis for developing students to become specialists and even subject matter experts for roles and careers in strategic and nuclear energy planning.

The curriculum and associated educational modules support capacity building and national human resource development in the nuclear energy sector.

The specific objectives of the course are to:

- provide knowledge and practical skills on the planning and modelling of scenarios of the NES evolution and on the use of the INPRO methodology for performing sustainability assessment of NESs, in order to assist Member States in long-range and

[4] The suggested educational modules provide a basis for different master's degree courses (some courses can be taken by PhD students) for different students depending on their main area of study and learning objectives defined by a particular university. Therefore, in this document, for simplicity, the term "the course" means a variety of such courses.

strategic planning for the development of nuclear energy programmes as part of their national energy mix;

- familiarize the students with the INPRO concept of NES sustainability in different areas, such as: economics, infrastructure, waste management, environment, proliferation resistance, reactor and fuel cycle safety, and provisions for further sustainability development and improvement by which substantial enhancements of sustainability in particular assessment areas could be evaluated and quantified;
- develop understanding of sustainability issues in a planned NES and ability to perform nuclear energy system analysis and assessment of the selected areas using the INPRO methodology criteria.

The students taking courses based on the INPRO model curriculum are expected to gain an understanding of general energy planning, the role of nuclear energy, the need and opportunity for utilizing innovation and new technologies, and ultimately become familiar with the INPRO methods and tools for NES modelling, analysis, and sustainability evaluation. As part of the model curriculum, INPRO can provide intensive support and detailed training material, thus enabling a university to move forward with the implementation of the model curriculum.

2.2. INTENDED AUDIENCE OF THE COURSE

The course modules developed by the IAEA-INPRO can broaden the curricula in university programmes beyond the technical components and include important economic, sustainability and policy elements that are instrumental in determining the use of nuclear energy. It is envisioned that this course can be particularly used in the education of masters-level students in nuclear science, nuclear technology, and nuclear engineering. This curriculum is suitable for graduates of programmes in nuclear science, engineering, and technology who plan to work in the nuclear industry.

The course is also useful for students studying international relations, political science and management, as well as a base for training on nuclear energy strategic planning and sustainability assessment (as part of a continuing education programme) for managers and technical professionals working in the nuclear industry.

2.3. PREREQUISITES FOR THE COURSE

This model curriculum outlines the educational modules directly related to strategic planning for sustainable nuclear energy development. It is assumed that students entering a master’s degree course that is based on the suggested educational modules possess prior knowledge and understanding of scientific concepts and principles necessary to successfully complete all academic requirements towards a graduate degree. Generally, the prerequisite for such a course is a bachelor’s degree in nuclear sciences or engineering. More specific prerequisites are discussed in Section 4 of this publication for each educational module. It is recommended that the course be included in a master’s programme for students already having a basic or intermediate level of nuclear knowledge.

3. DESCRIPTION OF THE MODEL CURRICULUM

3.1. METHODOLOGY EMPLOYED FOR DEVELOPING THE CURRUCULUM

This section summarizes the approach and methodology employed to create and further use the model curriculum on strategic planning for sustainable nuclear energy development.

The following were the main activities for the development of the model curriculum.

- Identifying needs for the educational course on strategic planning for sustainable nuclear energy development; these needs are discussed in Section 1 of the publication;
- Formulating the purpose and objectives of the course as defined in Section 2;
- Determining the intended audience and prerequisites for the course, which are discussed in Section 2;
- Creating a team of core experts and curricula developers;
- Identifying competency areas for course, described in detail in Section 3.2;
- Designing the model curriculum structure and developing an overall description of modules purposed for the educational coursework, presented in Section 3.3;
- Performing an initial design of module descriptions; these descriptions are included in Appendix I and contain the following data:
  - A short description of the module;
  - Learning objectives of the module, i.e. general statements about the larger goals expected to be achieved through teaching the module;
  - The prerequisites for each module;
  - Learning outcomes, i.e., specific statements that describe exactly what a student will be able to do in some measurable way upon completion of the module (a revised Bloom's taxonomy – see, for example, ref. [5] – was taken into consideration while formulating the learning outcomes);
  - Outline of module topics;
  - Suggested teaching delivery methods and considerations for student performance assessment, in particular:
    - Delivery methods such as lectures; practice (including practical exercises using handouts / job aids and simulation tools, seminars, structured discussions, fulfilling projects and research work performed individually or in a group, practice in various organizations, writing articles and research reports, and preparing diploma thesis); and self-study (including recommended reading, e-learning, fulfilling the assigned self-study exercises and self-check tests, and participation in various scientific and technical forums and networks);
    - Narrative briefly explaning the student performance assessment;
    - Estimate of the teaching hours.
  - Bibliography.

Based on the initial design of the model curriculum presented in this publication, the expectation is for follow-on activities as listed below.

— Consideration by interested educational organizations on the use of the model curriculum in their Master's courses and programmes;

— Design of courses and programmes at institutions using the model curriculum, which may require, a more detailed, customized design including:

  - Customizing and adapting the model curriculum to the needs and requirements of the educational organization;
  - Designing new courses or incorporating the customized curriculum into the existing courses and programmes;
  - Defining activities for the delivery of the modules, identifying specific lectures, practical exercises and self-study activities; and cross-referencing activities to the expected learning outcomes;
  - Defining learning modes (i.e., individual or group activities), learning settings (e.g., classroom, laboratory and simulation exercises, on-job practice in various organizations, or self-pacing), and particular teaching methods and tools;
  - Deciding on the student performance assessment methods (that may include quizzes, e.g., oral questioning or clicker activities; formal tests and examinations (oral, written or performance); evaluation of simulation exercises; observation and evaluation of individual and group performance during other practical exercises and discussions; observation of attitudes exhibited; and evaluation of projects performed individually or in a group).

— Developing and validating the teaching materials (for faculty staff / instructors and students) and performance assessment materials (e.g., the needed test items and tests);

— Assuring the availability of simulation and other software tools required for the development and use of teaching materials and for the implementation of particular modules;

— Assuring competence of the faculty / instructors delivering course material (including the appropriate selection and training, when needed);

— Piloting (trying-out) the selected parts of the developed course materials;

— Improving developed materials, competence of the faculty staff / instructors involved, and organizational aspects based on results from piloting the courses;

— Implementing courses and programmes using the developed and customized curriculum and teaching materials;

— Evaluating the conducted courses and programmes (including collecting and analysing feedback from students and faculty staff / instructors; analysing results of tests and examinations; administering surveys to the past students, faculty staff / instructors and organizations in which past students work; interviewing representatives of organizations that are the users of past students; and evaluating – as far as possible – an overall impact of the conducted courses and programmes on the sustainability of nuclear energy systems);

— Continuously improving quality and effectiveness of the educational courses and programmes (including the delivery methods, teaching materials and tools, competence of the faculty staff / instructors, and methodology).

The IAEA possess all necessary capabilities to assist Member States and their educational organizations in the development and use of the curriculum intended to strengthen strategic planning for sustainable nuclear energy development, that is discussed in more detail in Section 4 of the publication.

3.2. COMPETENCY AREAS

As mentioned in the Section 2, based on the model curriculum, universities can develop a range of master's degree courses using the INPRO training modules. As a result, students may acquire a variety of competences. The competency areas are categorized into the five groups described below[5].

Group 1 - Energy planning and strategies for sustainable development

This group includes the competencies related to understanding the sustainable development concept, energy planning for sustainable energy strategies, and evaluation of electricity and energy system options, energy investment planning, energy environment and climate policy formulation. This group explores the role of different technologies, including nuclear, in meeting the future energy needs and supporting sustainable development; methods and tools for planning sustainable energy development. Modules 1 and 5 (see Section 3.3 below) are designed to help develop these competences. Research projects on topics related to sustainable energy development under Module 7 would further enhance students' competence.

Group 2 - Planning for nuclear energy sustainability

This group includes the competences related to understanding of the concept of sustainable nuclear energy systems as developed by INPRO; the technical, economic, social and geopolitical aspects of nuclear energy; the international obligations and norms for peaceful application of nuclear technologies; potential role of nuclear energy for combating climate change; the INPRO approaches for scenario analysis and strategic planning for development of nuclear energy systems and the INPRO methodology for assessing sustainability of nuclear energy systems. For developing competences in this group, the students should opt for the Module 2 and Research Projects on topics related to sustainable nuclear energy under Module 7.

Group 3 - Innovations in nuclear energy sector in meeting sustainable energy development challenges

This group includes the competences related to understanding of the process of innovation and the evolution in the nuclear industry, as well as the need for technological and institutional innovations in the nuclear energy sector to achieve sustainability and to enhance the contribution of nuclear energy to sustainable development. It also includes good familiarity with recent and expected future advancements on nuclear reactor technologies and their fuel cycles, as well as non-electric applications. Also included in this group is awareness of the challenges and status of the development of fusion and hybrid fission-fusion technologies. Module 3 is intended to develop these competences.

Group 4 – Nuclear energy systems modelling and analysis

This group includes the competences related to developing long term scenarios for development and deployment of sustainable nuclear energy systems, understanding the approach for analysing complex interlinkages of performance, economics, and acceptability aspects of nuclear energy systems and comparative evaluation of various nuclear energy options based on problem structuring and the state-of-the-art judgement aggregation/uncertainty

[5] The specific competencies for each educational module are in Appendix I

analysis methods and key issues of, and plausible solutions for, the further improvement of NES sustainability, using system analysis tools. Module 6 helps develop these competences. Research Projects on topics related to sustainable nuclear energy under Module 7 would further enhance the depth of these competences.

Group 5 - The methodology for assessing sustainability of nuclear energy systems (the INPRO Methodology)

This group includes the competences related to understanding the INPRO methodology for performing a sustainability assessment which covers the following assessment areas: economics, environmental impacts, safety, proliferation resistance, waste management and infrastructure including physical protection. Each assessment area is comprised of a basic principle, user requirements and criteria The INPRO methodology is applicable to national or global nuclear energy systems and assessing their long-term sustainability. Module 4 is devoted to developing competences in applying the INPRO methodology.

3.3. CURRICULUM

The model curriculum is divided into three parts: core modules, advanced modules, and a research project module (Fig. 1). Universities may include these modules as part of the master's degree courses on strategic planning for sustainable nuclear energy development and may require that incoming students demonstrate relevant competence to enter an educational module based on previous coursework and/or professional experience.

Detailed description of each module is presented in Appendix I, including the expected learning outcomes, outlines of topics and recommended implementation approaches.

CORE MODULES

Module 1
Energy planning and strategies for sustainable development

Module 2
Planning for nuclear energy sustainability

Module 3
Innovations in the nuclear energy sector in meeting sustainable energy development challenges

ADVANCED MODULES

Module 4
Introduction to the INPRO methodology for assessing sustainability of nuclear energy systems

Module 5
Methods and tools for planning sustainable energy development

Module 6
Methods and tools for modelling and analysis of nuclear energy systems

RESEARCH PROJECT MODULE

Module 7
Research projects on planning and assessment of energy and nuclear energy systems

Fig. 1. Structure of the model curriculum.

3.3.1. Core modules

Module 1. Energy planning and strategies for sustainable development

Energy is essential to all human activities and critical to social and economic development. It is the engine of economic development. Lack of energy is a major contributing factor to the state of perpetual poverty for individuals and countries. Availability of affordable energy opens up many opportunities that drive economic development and accelerate social progress.

The present energy system on one hand suffers from stark disparities in terms of availability and affordability, and on the other hand causes substantial environmental damage and the dominant source of climate change because of its heavy dependence on fossil fuels. As such, the present energy system is not compatible with sustainable development. Today's choices about how energy will be produced and used in future would determine how energy system can be made sustainable and, thereby, support socioeconomic progress that can be sustained.

This module, consequently, is designed to develop a deep understanding of comparative evaluation of various energy options in terms of their technical, economic and environmental characteristics, and formulate sustainable energy strategies for a country/region by taking into account technical, economic, environmental, social and political aspects, and evaluating the potential role of various energy resources and technologies in meeting future energy needs for sustainable development.

The main topics covered in this module are:

- Concept of Sustainable Energy System;
- Global Energy Supply-Demand Trends;
- Energy Resources;
- Energy Technologies (technical, economic, and environmental characteristics);
- Energy Economics;
- International Energy Trade & Prices;
- Energy Security;
- Climate Change;
- Social Aspects of Energy;
- Geo-political Considerations for Energy;
- Methods and Tools for Planning Sustainable Energy Development.

Module 2. Planning for nuclear energy sustainability

The world has recognized the need for transforming the present energy system to make it compatible with sustainable development. There are several energy technologies, existing and new ones, that can support sustainable development. Nuclear power is one such option that offers reliable, economic and safe carbon-free electricity generation. Not only is nuclear power a mature energy technology, substantial advancements are emerging to further improve safety, economic competitiveness and social acceptability. It has recently been included in the EU Taxonomy for sustainable activities[6].

This module is intended to familiarise the students with the concept of sustainable nuclear energy systems as developed by INPRO, and to develop understanding of the technical, economic, social and geopolitical aspects of nuclear energy. The module will also explain the international obligations and norms for peaceful application of nuclear technologies, and will describe the INPRO approaches for analysing and assessing sustainability of nuclear energy systems.

The main topics covered in this module are:

- Introduction to Sustainable Nuclear Energy Systems;
- Nuclear Power Reactors and Fuel Cycles;
- Economics of Nuclear Power;
- Risks and Benefits of Nuclear Energy;
- Role of Nuclear Power in Combating Climate Change;
- Public Acceptance of Nuclear Energy;
- Geopolitical Considerations for Nuclear energy;
- International Obligations and Norms for Peaceful uses of Nuclear Energy;
- Overview of INPRO Methodology for Analysing and Assessing Sustainability of Nuclear Energy Systems (including the Introduction of INPRO Tools for Planning, Analysis and Assessment of Nuclear Energy Systems).

Module 3. Innovations in the nuclear energy sector in meeting sustainable energy development challenges

This module is dedicated to presenting an overview of the innovation process and the importance of both technological and institutional innovations in the nuclear energy sector; explaining the current nuclear-power reactors and fuel cycles their up-to-date improvement and evolutionary/revolutionary examples; and gaining familiarity with future types of nuclear-power reactors and fuel cycles. The module includes brief information about approaches and methods for foresight (prediction) to future technologies. The outcome will be a good understanding of the contribution of technological and institutional innovations towards improvements that will lead to achieving nuclear energy sustainability and to increasing the contribution of nuclear energy to sustainable development goals.

The main topics covered in this module are:

- Innovation process and the need for technological and institutional innovations. Research and development (R&D) as the basis for innovations, technical and instrumental basis for R&D.
- Main technical features of early and current nuclear energy technologies and their fuel cycles.
- Examples of technology improvement (revolutionary and evolutionary) as result of R&D and other efforts.

[6] https://ec.europa.eu/info/publications/220202-sustainable-finance-taxonomy-complementary-climate-delegated-act_en

- Distinct features of future nuclear energy technologies and their fuel cycles and their impact on economics, natural resource use, infrastructure and safety, waste management, proliferation resistance, and other aspects.
- Introduction to fusion and hybrid fission-fusion systems.
- Past and current institutional innovations in the nuclear energy sector,
- The need for future institutional innovations and enhanced international cooperation to improve sustainability of nuclear energy systems.
- Foresighting possible future technological and institutional innovations.

3.3.2. Advanced modules

Module 4. Introduction to the INPRO methodology for assessing sustainability of nuclear energy systems

The module presents a set of basic principles, user requirements and criteria, together with an assessment method. These constitute the INPRO methodology for the evaluation of a national, regional, or global nuclear energy system and its long-term sustainability. The INPRO methodology covers the six topical areas for the assessment of NES sustainability: environmental impacts, safety, proliferation resistance, waste management, infrastructure (including physical protection), and economics.

The main topics covered in this module are:

- Holistic approach of INPRO methodology;
- Environmental impacts (resource depletion and stressors);
- Safety (reactors and fuel cycle);
- Proliferation resistance;
- Waste management;
- Infrastructure (including physical protection);
- Economics.

Module 5. Methods and tools for planning sustainable energy development

In order to explore paths to sustainable energy development and evaluate the possible outcome of future energy decisions, a systematic framework is needed that facilitates assessment of energy supply and use technologies, identification of linkages within the energy system as well as with economy and society, estimation of trade-offs and comparison of consequences of alternative. The IAEA energy planning models offer such a framework. The IAEA is helping countries to build local expertise to design and evaluate alternative energy strategies that supports national sustainable development goals.

This module introduces the IAEA energy planning models. The student will become familiar with the concepts, methodologies and application of these energy models.

The main topics covered in this module are:

- Energy Chains and Energy System;
- Scenario Development Approach;
- Main Drivers of Energy Demand;
- Model for Analysis of Energy Demand (MAED);

- Assessment of Energy Resource and Supply Potential;
- Considerations in Energy Supply Strategies;
- Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE);
- External Costs of Energy Supply Chains;
- Simplified Approach for Estimating Impacts of Electricity Generation (SIMPACTS);
- Evaluating financial viability of energy projects (FINPLAN);
- Indicators for Sustainable Energy Development (ISED).

Module 6. Methods and tools for modelling and analysis of nuclear energy systems

The module provides a broad understanding of the concepts and approaches of the INPRO Analysis Support for Enhanced Nuclear Energy Sustainability (ASENES). This module covers:

(1) the framework for modelling scenarios for the evaluation of nuclear energy systems, and associated tools to address the key issues and plausible solutions for nuclear energy sustainability continuous improvement and enhancement;
(2) tools for the economic evaluation of alternative nuclear energy systems to compare competitiveness of NES alternatives;
(3) comparative evaluations of nuclear energy systems or scenarios, based on problem structuring and the state-of-the-art methods and tools for judgement aggregation/uncertainty analysis to support a multi-criteria selection of a nuclear energy system.

The following is a list of the main topics covered in this module.

- Introduction to INPRO approaches and tools for modelling and analysis of nuclear energy systems
- INPRO framework for NES scenario modelling and analysis
- Basics for NES mass flow and economic analysis
- NES Simulators - simple models of a nuclear energy system
- Modelling of nuclear energy systems with MESSAGE-NES
- NES roadmapping and ROADMAPS-ET
- Multi-criteria decision making for judgment aggregation
- Comparative evaluation of NES options with the use of multi-criteria decision analysis (MCDA): the Key Indicators for Innovative Nuclear Energy System (KIND) approach and tool
- NESA Economics Support Tool (NEST).

3.3.3. Research project module

Module 7. Research projects on planning and assessment of energy and nuclear energy systems.

The module involves the fulfilment of research projects on planning and assessment of overall energy systems and, in particular NES, in selected topical areas relevant to strategic planning for the sustainable nuclear energy development, which can be carried out as part of the curriculum. Completion of these projects can be through coursework, small or comprehensive projects performed by students individually or in a group, work carried out during internships, and within preparing a thesis that is part of a master's programme or doctoral thesis.

4. IAEA SUPPORT FOR THE MODEL CURRICULUM IMPLEMENTATION

4.1. OVERALL SCOPE OF IAEA POTENTIAL SUPPORT

The IAEA can provide support to interested educational organizations in its Member States for implementation of the model curriculum. This support can be provided in the following areas:

— Providing IAEA tools for energy analysis and planning, to support nuclear energy modelling and analysis.

— Training on IAEA methods, models and software tools in the field of energy analysis and planning, and in the field of nuclear energy modelling and analysis; (this training may be needed for the faculty staff of educational organizations or for students undertaking research projects with the use of IAEA tools).

— Providing training/teaching materials for educational organizations for developing, using, customizing or adapting teaching material employing the model curriculum;

— Designing of educational courses using the model curriculum, and in the development or customization of teaching material;

— Piloting selected parts of educational courses that employ the model curriculum;

— Implementing educational courses with the model curriculum (e.g. through involving experts in specialized areas);

— Organizing internships at the IAEA for practical study of subjects associated with the model curriculum;

— Performing scientific visits and fellowships to organizations possessing valuable and proven expertise in planning for sustainable nuclear energy development (these scientific visits and fellowships may be helpful for the faculty staff and specialists participating in the development of teaching materials and implementation of courses based on the model curriculum);

— Providing access to INPRO resources on the IAEA Cyber Learning Platform for Nuclear Education and Training (CLP4NET);

— Providing IAEA relevant publications (either through downloads at www.iaea.org/publications, or through an order request to the IAEA).

It should be particularly mentioned that the IAEA can support in strengthening the expertise of teachers by arranging specialised workshops, for example, through participation in INPRO School on Nuclear Energy Strategic Planning.

4.2. ANALYTICAL TOOLS TO SUPPORT ENERGY ANALYSIS AND PLANNING

Long-range and strategic planning for energy and identification of the potential role of nuclear energy require a sound understanding of the dynamics of social and economic development; technological innovations; and interlinkages of energy infrastructures, environmental constraints and climate change mitigation. In particular, elaborating sustainable energy development necessitates a comprehensive analysis of all energy options in terms of their social, economic, and environmental implications. Such an analysis is only possible with the help of an integrated framework. The IAEA developed a set of computer-based energy models which provide a consistent framework for formulating long-term energy strategies and evaluating the potential role of various energy options, including nuclear energy, and designing sustainable energy systems. These energy models encompass the entire energy system starting from the extraction of natural energy resource – both depletable and renewable – to conversion, transportation and distribution, and final energy use at the consumers' end. These energy models are constantly being enhanced and improved by the IAEA to keep them suitable for addressing emerging issues. A well-established mechanism is in place to transfer these energy models to Member States along with intensive support for local capacity building in the use of these models, especially to determining national energy strategies for sustainable energy development. Appendix II contains a brief description of the IAEA energy planning models.

4.3. ANALYTICAL TOOLS TO SUPPORT NUCLEAR ENERGY MODELLING AND ANALYSIS

If a Member State determines that nuclear energy is a needed component of its sustainable energy system, the IAEA can provide intensive support for developing a national nuclear energy programme. A nuclear energy programme is a long-term national commitment, for comprehensive planning of all phases of the programme and establishing necessary infrastructure.

In order to design a national strategy for the development of a nuclear energy programme, evaluation of various nuclear technology alternatives has to be undertaken, involving economic competitiveness, natural resource use, waste generation, environmental impacts, required safety and needed infrastructure, proliferation resistance, public acceptance, and other factors. INPRO has developed several tools to facilitate such analysis and evaluation of nuclear energy alternatives. The INPRO tools for analysing nuclear energy alternatives are briefly described in Appendix II.

4.4. HOW TO OBTAIN THE IAEA TOOLS

The IAEA tools to support (i) energy analysis and planning and (ii) nuclear energy modelling and analysis are available to all Member States of the IAEA. The tools support capacity building in the public sector. These tools are also very effective for academic activities including research and teaching.

Governmental agencies, research and development organizations, educational institutions, and operating organizations can obtain IAEA tools at no cost. The IAEA will provide the requester with a licence agreement form for the requested tools, which must be duly filled, signed, and sent back as a scanned pdf document via email. The two contacts for IAEA tools are:

- PESS.Contact-Point@IAEA.org, Planning and Economic Studies Section, for energy analysis and planning tools
- INRPO.Tools@IAEA.org, INPRO Section, for nuclear energy modelling and analysis

4.5. TRAINING ON THE IAEA TOOLS

The IAEA assists the Member States in capacity building related to long-range and strategic planning for nuclear energy programmes. The IAEA education and training activities help prepare the next generation of professionals to manage complex nuclear power programmes. The IAEA offers a broad spectrum of education, training activities and capacity-building programmes. These services include face-to-face training courses and workshops, as well as online learning on various topics related to sustainable energy planning.

The IAEA's capacity building programmes for sustainable energy development help developing countries and economies in transition building their energy planning capabilities with respect to all three pillars of sustainable development – economic, environmental, and social. These programmes include providing extensive training to local professionals on the use of IAEA's energy planning models and guidance for conducting national studies to identify the role of various technologies, including nuclear, in meeting a country's future energy needs. This support includes elaborating sustainable energy strategies and conducting studies for energy system and electricity sector development and management, energy investment planning and energy environment policy formulation.

The IAEA regularly arranges educational and training courses in which subject matter experts provide informative and hands-on training on the use of the IAEA tools. The INPRO Section of the IAEA conducts INPRO schools, where young professionals, university teachers, postgraduates and researchers learn about sustainability issues and planning for nuclear energy system. Within the INPRO schools, the IAEA and international experts share their insights and experience to familiarize the participants with the INPRO concepts, methodology and tools. The participants receive introductory training on the planning, modelling, analysis and sustainability assessment of nuclear energy systems and the fundamentals of nuclear economics. The INPRO School programme covers in a concise form the topics of the educational modules of the curriculum presented in Appendix I.

These training events are held at the IAEA Headquarters in Vienna, Austria, and in the IAEA Member States. Organizations and individuals interested in participating in these training events should check the IAEA events page at https://www.iaea.org/events/ regularly.

Organizations of INPRO Members[7] interested in hosting and supporting national or regional INPRO schools should contact their national INPRO representative. The national INPRO representative will then present this request at an annual INPRO Steering Committee Meeting.

4.6. THE CYBER LEARNING PLATFORM FOR NETWORK EDUCATION AND TRAINING

One of the roles of the IAEA within the INPRO framework is to establish and maintain tools and mechanisms to help facilitate implementation of INPRO training activities. The on-line platform is an important tool and a collaborative mechanism for sharing and archiving educational and training materials in the nuclear field, including educational materials on the model curriculum for strategic planning of sustainable nuclear energy systems.

On-line collaborations within the INPRO framework is supported by the cyber learning platform CLP4NET developed by the IAEA. This allows Member States access to nuclear

[7] INPRO membership consists of 44 Members (as of September 2022) – 43 IAEA Member States and the European Commission (EC): Algeria, Argentina, Armenia, Bangladesh, Belarus, Belgium, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, Egypt, France, Germany, Ghana, India, Indonesia, Israel, Italy, Japan, Jordan, Kazakhstan, Kenya, Republic of Korea, Malaysia, Mexico, Morocco, Netherlands, Pakistan, Poland, Romania, Russian Federation, Slovakia, South Africa, Spain, Switzerland, Thailand, Turkey, Ukraine, United States of America, Uzbekistan, Vietnam and the EC.

education and training resources or to host the delivery of such resources in the form of self-directed or supervised courses or e-learning.

Many INPRO resources are made available through the CLP4NET. These resources are available to universities, centres of excellence, vocational education organizations and other interested entities implementing the model curriculum. The process of sharing materials involves the IAEA which consults, as appropriate, with external providers of educational material (such as universities). Access to some INPRO resources may be open to registered nuclear sector users (e.g., registered NUCLEUS[8] users).

The CLP4NET provides three main functions for educational organizations. The first main function is to archive educational materials contributed by the IAEA or by organizations implementing the module curriculum.

The second main function of the CLP4NET is to offer an e-learning environment to support instructor-controlled self-study. Educational organizations (e.g. universities) offering courses on the basis of the model curriculum can use any platform to provide e-learning instructor-controlled courses. However, universities are encouraged to use the CLP4NET because of the benefits it provides in terms of sharing educational resources. With the CLP4NET, teachers provide e-learning courses, and they can monitor students' progress.

The third main function of the CLP4NET is to provide the on-line learning capabilities. E-learning that can support a self-study within various modules of the model curriculum is available through the IAEA Learning Management System at https://elearning.iaea.org/m2/. On-line e-learning is available in different areas including nuclear technology and applications, nuclear safety and security, and safeguards and verification.

[8] NUCLEUS (https://nucleus.iaea.org/) is a common access point to the IAEA information resources including databases, web sites, applications, publications, safety standards and training materials.

APPENDIX I. DESCRIPTION OF THE EDUCATIONAL MODULES

I.1. MODULE 1. ENERGY PLANNING AND STRATEGIES FOR SUSTAINABLE DEVELOPMENT

I.1.1. Short description

Sustainability of the energy sector is indispensable for achieving the overall sustainable development. A range of energy technologies and resources are available, which can be used for meeting the future energy needs. What mix of these energy technologies and resources would ensure sustainability of the energy sector in particular country conditions depends on a number of factors, including domestic energy resources, technical, economic and environmental characteristics of various energy options, as well as their social acceptability, and geopolitical consideration. Additionally, to formulate sustainable energy strategies for a country or region, it is vital that the long-term implications of alternative energy options are evaluated and an optimal contribution of various energy resources and technologies is determined in meeting future energy needs for sustainable development.

This module describes the concept of sustainable energy development and the central role of the energy sector in achieving the overall sustainable development in a country or region. It also explains the prevailing and emerging issues related to sustainable energy development, including energy access and affordability, energy security, energy trade, geopolitics, and climate change. The module introduces the IAEA's energy models for elaborating and evaluating energy strategies and their compatibility with sustainable development [10].

The following is a list of the main topics in this module.

- Concept of a sustainable energy system
- Global energy supply-demand trends
- Energy resources
- Energy technologies (technical, economic and environmental characteristics)
- Energy economics
- International energy trade and prices
- Energy security
- Climate change
- Social aspects of energy
- Geopolitical considerations for energy
- Methods and tools for planning sustainable energy development

I.1.2. Learning objectives

The main objectives of this module are the following.

- Establish an understanding of the technical, economic, environmental, social and geopolitical considerations in the development of sustainable energy strategies for a country or a region.
- Familiarize students with an evaluation of potential roles of various energy resources and technologies in meeting future energy needs for sustainable development.

I.1.3. Prerequisites

The students are expected to possess a basic knowledge of mathematics, physics and energy technologies. An engineering background is advantageous but not mandatory.

I.1.4. Learning outcomes

On completion of this module, the students are expected to have a deep understanding of the main considerations in evaluating energy choices for national energy strategies for sustainable development. The students will garner an awareness of the geopolitical considerations for energy security and international energy trade. The students will be familiar with methods and tools for conducting evaluation of various energy technologies in terms of their technical, economic, and environmental characteristics, as well as factors that influence the societal acceptability of energy technologies.

The students, upon completion of the module, are expected to be able to demonstrate knowledge, abilities and behaviours defined in Table I.1.1.

TABLE I.1.1. LEARNING OUTCOMES UPON COMPLETION OF THE MODULE

No	Expected learning outcomes
1	Explain the main aspects that need to be considered in evaluating the energy choices for national energy strategies for sustainable development plans.
2	Express familiarity with energy resources, energy technologies and their technical, economic and environmental characteristics.
3	Demonstrate understanding of energy economics and methodology for economic comparison of various energy options.
4	Illustrate awareness of the geopolitical considerations for energy security and international energy trade.
5	Demonstrate familiarity with the methods and tools available for conducting evaluation of various energy technologies in terms of their technical, economic and environmental characteristics, and for developing sustainable energy strategies.

I.1.5. Outline of module topics

Below is a list of the main topics covered in the module.

- **Concept of sustainable energy system**

  Explanation of sustainable energy system based on the overall concept of sustainable development, including the importance of energy for social and economic progress. Explanation of the Sustainable Development Goal (SDG) 7 'Affordable and Clean Energy' and its linkage with all other SDGs.

- **Global energy supply-demand trends**

  Explanation of the historical evolution of energy supply and demand patterns with details of changes in the global energy supply mix and the expected future trends. Description of global and regional energy scenarios developed by leading institutions including IEA/OECD, IIASA, IRENA and IPCC.

— **Energy resources**

Difference between depletable and non-depletable energy resources. Global availability of energy resources and their geographical distribution. Categorization of energy resources on the basis of quality and cost.

— **Energy technologies (technical, economic and environmental characteristics)**

Description of energy technologies for resource extraction, conversion, transportation and distribution, and end uses of energy. Comparison of all these energy technologies in terms of their technical, economic and environmental characteristics.

— **Energy economics**

Description of the basic concepts for economic analysis. Explanation of the commonly used metrics for evaluation of energy alternatives – Net Present Value, Benefit to Cost Ratio, Levelised Unit Cost of Energy, and others. Explanation of possible system level impacts on economic competitiveness of alternative energy options.

— **International energy trade and prices**

Review of historical trends in international energy trade and prices, major obstacles to international trade and main factors causing price volatility. Future prospects of international energy trade and prices.

— **Energy security**

Explanation of the concept of energy security for energy imports and energy exporters. Description of the main factors threatening energy security and the role of energy security for sustainable energy development.

— **Climate change**

Description of the climate change phenomenon and the role of energy in climate change. Comparison of energy sources and technologies in terms of their greenhouse gas (GHG) emissions. Technical and economic features of carbon capture technologies. Understanding of international efforts to combat climate change and related international agreements.

— **Social aspects of energy**

Review of public acceptability of various energy technologies. Description of risk perceptions of energy technologies and comparison of public health impacts of energy sources.

— **Geopolitical considerations for energy**

Description of geopolitical issues and challenges for energy, and a need for international and regional cooperation.

— **Methods and tools for planning sustainable energy development**

Introduction of the IAEA's energy planning models – Model for Analysis of Energy Demand (MAED), Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE), Wien Automatic System Planning Package (WASP), Model for Financial Analysis of Electric Sector Expansion Plans (FINPLAN), Simplified Approach for Estimating Impacts of Electricity Generation (SIMPACTS), Indicators for Sustainable Energy Development (ISED).

I.1.6. Suggested teaching delivery methods and student performance assessment

Delivery of this module will be through lecturing, practical exercises, structured discussions, and self-study. E-learning will be part of the self-study. Students will develop deeper understanding through self-study of the recommended reading material. The total learning hours for this module which include time for the scheduled teaching activities and self-study are estimated as thirty-one (31) hours; although, a more intensive self-study may result in increasing the learning hours.

The student performance assessment may use the following methods: short entry and exit written (preferably computerized) tests, oral questioning and clicker activities within the conducting of teaching on particular topics, short essays, observation and evaluation of students' performance during practical exercises and discussions, presentations at the seminars, and observation of attitudes exhibited.

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I.2. MODULE 2. PLANNING FOR NUCLEAR ENERGY SUSTAINABILITY

I.2.1. Short description

The IAEA/INPRO section developed a notion for defining a sustainable nuclear energy system based on the overall concept of sustainable development [11]. This module elaborates on the technical features of various nuclear power reactor and nuclear fuel cycle technologies, and their sustainability. The module presents a methodology for evaluating economic competitiveness of nuclear energy systems and for identifying the potential role of nuclear energy for combating climate change. It also discusses the factors influencing public acceptance of the nuclear energy and geopolitical considerations. The module also explains the international obligations and norms for peaceful application of nuclear technologies.

The main topics addressed in this module are the following.

- Introduction to sustainable nuclear energy systems
- Nuclear power reactors and fuel cycles
- Economics of nuclear power
- Risks and benefits of nuclear energy
- Role of nuclear power in combating climate change
- Public acceptance of nuclear energy
- Geopolitical considerations for nuclear energy
- International obligations and norms for peaceful uses of nuclear energy
- Overview of INPRO methodology for analysing and assessing sustainability of nuclear energy systems (including the introduction of INPRO tools for planning, analysis and assessment of nuclear energy systems)

I.2.2. Learning objectives

The main objectives of this module are the following.

- Familiarise students with the concept of sustainable nuclear energy systems based on the UN concept and developed by INPRO
- Develop an understanding of the technical, economic, social, environmental and geopolitical aspects of nuclear energy
- Explain the international obligations and norms for peaceful application of nuclear technologies
- Describe the INPRO methodology for analysing and assessing sustainability of nuclear energy systems

I.2.3. Prerequisites

The students are expected to fulfil the following prerequisites for entering this module:

- Possess a basic knowledge of mathematics, physics, and nuclear power technologies; an engineering background (including a bachelor’s degree in nuclear engineering) is advantageous.
- Successful completion of core module 1 ‘Energy planning and strategies for sustainable development’ of the model curriculum or a module or course with similar content.

I.2.4. Learning outcomes

The students, upon completion of the module, are expected to have demonstrated the knowledge, abilities and behaviours defined in Table I.2.1.

TABLE I.2.1. LEARNING OUTCOMES UPON COMPLETION OF THE MODULE

No	Expected learning outcomes
1	Explain the concept of sustainable nuclear energy systems as developed by INPRO and presented in relevant IAEA publications.
2	Relate the INPRO concept of sustainable energy systems to the sustainable energy development for achieving Sustainable Development Goals (SDGs).
3	Describe the technical and economic features of various nuclear power technologies, including their respective fuel cycles, using the module teaching materials.
4	Discuss the potential role that nuclear energy can play in combating climate change.
5	Summarize potential benefits and major risks induced by the use of nuclear energy.
6	Illustrate the importance of public acceptance of nuclear energy using examples from different countries and stating main factors influencing public acceptance of nuclear power.
7	Describe sensitivities related to nuclear technologies and material.
8	List main national responsibilities and obligations for peaceful uses of nuclear energy.
9	Summarize the essence of international conventions governing peaceful uses of nuclear energy.
10	Describe briefly the INPRO methodology for analysing and assessing sustainability of nuclear energy systems, using the IAEA publications and module teaching materials.
11	Demonstrate valuing the planning for the sustainability of a nuclear energy system.

I.2.5. Outline of module topics

The module includes the following topics listed below.

- **Introduction to sustainable nuclear energy systems**

  Description of the sustainable nuclear energy concept as elaborated by IAEA/INPRO, and a linkage of the concept with sustainable energy and overall sustainable development, as well as an explanation of the role of sustainable nuclear energy in achieving UN Sustainable Development Goals (SDGs) [12].

- **Nuclear power reactors and fuel cycles**

  Review of historical development of nuclear power reactor and associated fuel cycle technologies; comparison of technical features (performance, safety, natural resource use, wastes generated, proliferation resistance) of these technologies; and improvements achieved in the past and expected in future.

— **Economics of nuclear power**

Description of the cost structure of a nuclear power plant, methodology for evaluation of economic competitiveness of a nuclear power project, and main economic risks for a nuclear power project. Explanation of system level effects on economic competitiveness of a nuclear power plant, and macro-economic impacts of introducing or expanding nuclear power programmes.

— **Risks and benefits of nuclear energy**

Review of the potential benefits of nuclear power in terms of energy affordability, reliability and security, environmental preservation, and climate change, as well as spinoff benefits such as industrial development, and scientific and technical research progress. Review of major risks (e.g., in regard to technical and economic performance, safety and security challenges, waste management, and proliferation concerns).

— **Role of nuclear power in combating climate change**

Description of the role of energy sector in climate change and comparison of greenhouse gas (GHG) emissions from different energy sources. Comparison of cost-effectiveness of different energy options for mitigating GHG emission, and presentation of the potential role of nuclear power in combating climate change.

— **Public acceptance of nuclear energy**

Review of the historical progression of public perception about nuclear power; and impact of major nuclear accidents on public perception. Comparison of public acceptance of nuclear power in different countries and identification of various factors influencing public acceptance of nuclear power.

— **Geopolitical considerations for nuclear energy**

Description of sensitivities related to nuclear technologies and material, and geopolitical consideration in the use of nuclear energy.

— **International obligations and norms for peaceful uses of nuclear energy**

Review of national responsibilities and obligations for peaceful uses of nuclear energy. Explanation of international conventions governing peaceful uses of nuclear energy.

— **INPRO methodology for analysing and assessing sustainability of nuclear energy Systems**

Overview of the INPRO methodology for analysing and assessing sustainability of nuclear energy systems (including the introduction of INPRO tools for planning, analysis and assessment of nuclear energy systems).

I.2.6. Suggested teaching delivery methods and student performance assessment

Delivery of this module will be through lecturing, practical exercises, structured discussions, and self-study. The total learning hours for this module which include time for the scheduled teaching activities and self-study are estimated as thirty-two (32) hours; although, a more intensive self-study may result in increasing the learning hours.

The student performance assessment may use the following methods: short entry and exit written (preferably computerized) tests, oral questioning and clicker activities within the conducting of teaching on particular topics, observation and evaluation of students' performance during practical exercises and discussions, and observation of attitudes exhibited.

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I.3. MODULE 3. INNOVATIONS IN THE NUCLEAR ENERGY SECTOR IN MEETING SUSTAINABLE ENERGY DEVELOPMENT CHALLENGES

I.3.1. Short Description

Nuclear energy systems — including nuclear power reactors and fuel cycle technologies — have undergone substantial improvements over the past decades. For example, increased technical performance of nuclear power reactors, enhanced safety, improvements in waste management, strengthened non-proliferation, and other enhancements. These advancements in nuclear was possible through technological and institutional innovations. The nuclear industry is still striving for further improvements and faces emerging challenges to ensure sustainability of nuclear energy. Technological and institutional innovations will be critical components of future nuclear energy systems' sustainability including improved economic competitiveness, efficient use of natural resources, reducing radioactive waste, and addressing safety, security, and non-proliferation. This module reviews the recent innovations and will identifies the necessary future developments for continuous enhancement of sustainability in the use of nuclear energy.

The main topics addressed in this module are as follows:

- The innovative process and the need for technological and institutional innovations. Research and development (R&D) as the basis for innovations. Technical and instrumental basis for R&D.
- Main technical features of early and current nuclear energy technologies and their fuel cycles.
- Examples of technology improvements (revolutionary and evolutionary) as a result of R&D and other efforts.
- Distinct features of future nuclear energy technologies and their fuel cycles, along with their impact on economics, natural resource use, infrastructure and safety, waste management, proliferation resistance, and other aspects.
- Introduction to fusion and hybrid fission-fusion systems.
- Past and current institutional innovations in the nuclear energy sector.
- The need for future institutional innovations and enhanced international cooperation to improve sustainability of nuclear energy systems.
- Foresighting potential future technological and institutional innovations.

I.3.2. Learning objectives

The main objective of this module is:

- to describe the needs for technological and institutional innovations and improvements in nuclear energy systems with the goal to achieve sustainable development and deployment.

I.3.3. Prerequisites

The students are expected to possess a basic knowledge of mathematics, physics and nuclear power technologies. Successful completion of Module 2 'Planning for nuclear energy sustainability' is also an essential prerequisite.

I.3.4. Learning Outcomes

On completion of this module, the students are expected to have adequate understanding of the innovation process and the need for technological and institutional innovations in the nuclear energy sector to achieve sustainability. This will be attained through familiarity with the recent advancements in nuclear reactor technologies, including their fuel cycles and expanded use of nuclear energy for non-electrical applications. The students will have an appreciation of innovations needed in the institutional arrangements at national and international levels, and awareness of challenges and development status of fusion and hybrid fission-fusion technologies.

The students, upon completion of the module, are expected to have demonstrated the knowledge, abilities and behaviours defined in Table I.3.1.

TABLE I.3.1. LEARNING OUTCOMES UPON COMPLETION OF THE MODULE

No	Expected learning outcomes
1	Explain the process and the role of innovations for developing and deploying nuclear energy systems and ensuring their sustainability.
2	Describe the role of technological innovations for transition to future sustainable nuclear power reactors and fuel cycles.
3	Express understanding of the role of institutional innovations for sustainable nuclear energy development and deployment.
4	Describe the interlinkage of technical and institutional innovations in enhancing the role of nuclear energy.
5	Demonstrate an understanding of the role of innovations for improvements in economics, natural resource use, safety, proliferation resistance, waste management, and non-power applications of nuclear energy.
6	Illustrate familiarity with the development status of fusion and hybrid fission-fusion technologies.

I.3.5. Outline of module topics

The main topics of the module cover the following subjects:

- **The process of innovation and how it applies to nuclear energy systems**
  - Definition of innovation and examples
  - Stages of innovation as applied to nuclear energy, and the roles and interactions of relevant organizations and institutions
  - The role of technological and institutional innovations

- **Technological innovations: past, present, and future needs to achieve sustainability and to enhance the contribution of nuclear energy to sustainable development goals**
  - Early nuclear technologies and applications
  - Current nuclear energy technologies and applications
  - Technologies under development
  - Contribution of technological innovation to sustainability

- **Institutional innovations: past, present and future needs to achieve sustainability and to enhance the contribution of nuclear energy to sustainable development goals**
  - The roles of various institutions
  - The importance of international cooperation
  - Institutional innovations: past and present
  - Institutional innovations: future needs to achieve sustainability and to enhance nuclear contribution to sustainable development

- **Technological and institutional innovations are interlinked and provide enhancements in**
  - Economics
  - Natural resources and reduction of impact on environment
  - Safety and nuclear security
  - Proliferation resistance
  - Expanding the use of nuclear energy to meet increasing global energy demand

- **Fusion – development status of fusion and hybrid fission-fusion**
  - Introduction to fusion and hybrid fission-fusion systems
  - Issues and development status of fusion and hybrid fission-fusion technologies

- **Foresighting technological and institutional development**
  - Identifying potential future development on the technological front and at the institutional side in nuclear energy.

I.3.6. Suggested teaching delivery methods and student performance assessment

This module may be taught through: lecturing and seminars by professors or subject matter experts; practical exercises; structured discussions; and self-study by students. The total learning hours for teaching this module material are estimated as thirty-four (34) hours for lectures; additionally certain time for seminars; and sufficient time (about 30 hours) for self-pacing activities, although, a more intensive self-study may be needed.

The student performance assessment may be performed using the following methods: short entry and exit written (preferably computerized) tests, oral questioning and clicker activities within a conducting of teaching on particular topics, short essays, observation and evaluation of students' performance during practical exercises and discussions, presentations at the seminars, and observation of attitudes exhibited.

I.3.7. Bibliography

INTERNATIONAL ATOMIC ENERGY AGENCY, Innovation in nuclear is key for a sustainable energy future, IAEA Bulletin, November 2017, by William D. Magwood, IV (2017).

US DEPARTMENT OF ENERGY, 3 Innovations Transforming the Nuclear Industry, Office of Nuclear Energy, US Department of Energy, June 2018. https://www.energy.gov/ne/articles/3-innovations-transforming-nuclear-industry

NUCLEAR ENERGY AGENCY, ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, Innovation in Nuclear Energy Technology, Nuclear Energy Agency, Organisation for Economic Cooperation and Development, OECD Publications, NEA No. 6103, Paris (2007).

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I.4. MODULE 4. INTRODUCTION TO THE INPRO METHODOLOGY FOR ASSESSING SUSTAINABILITY OF NUCLEAR ENERGY SYSTEMS

I.4.1. Short description

This module presents the INPRO tool - a set of basic principles, user requirements and criteria, together with an assessment approach. This assessment approach constitute the INPRO methodology for the assessment of a national or global nuclear energy system and its long-term sustainability. The IAEA/INPRO methodology covers the six topical areas for the assessment of NES sustainability: environmental impacts, safety, proliferation resistance, waste management, infrastructure (including physical protection), and economics.

The main topics addressed in this module are as follows:
- Holistic approach of INPRO methodology;
- Environmental impacts (resource depletion and stressors);
- Safety (reactors and fuel cycle);
- Proliferation resistance;
- Waste management;
- Infrastructure (including physical protection);
- Economics.

I.4.2. Learning objectives

The main objectives of this module are:

- to familiarise the students with the concept of the INPRO methodology for assessing sustainability of nuclear energy systems;

- to develop understanding of a set of basic principles, user requirements and criteria, together with an assessment approach, which constitute the INPRO methodology;
- to explain how the INPRO methodology is used for assessing national or global nuclear energy systems regarding their long-term sustainability;
- to present and discuss case studies on practical application of the INPRO methodology.

I.4.3. Prerequisites

The students are expected to fulfil the following prerequisites for entering this module:

- Possess a basic knowledge of mathematics, physics, and nuclear power technologies; an engineering background or/and bachelor in nuclear engineering is advantageous;
- Successfully complete a core module 2 'Planning for nuclear energy sustainability' of the module curriculum; a familiarity with Modules 1 and 3 is strongly recommended.

I.4.4. Learning outcomes

The students, upon completion of the module, are expected to demonstrate the knowledge, abilities and behaviours defined in Table I.4.1.

Table I.4.1. LEARNING OUTCOMES UPON COMPLETION OF THE MODULE

No	Expected learning outcomes
1	Explain the basic terms and approaches in the six topical areas relevant to the assessment of the nuclear energy system (NES) sustainability: environmental impacts, safety, proliferation resistance, waste management, infrastructure (including physical protection), and economics.
2	Discuss briefly the concept of the INPRO methodology as a holistic sustainability assessment tool in the areas of environmental impacts, safety, proliferation resistance, waste management, infrastructure (including physical protection), and economics as presented in relevant IAEA publications, summarizing the methodology potential benefits.
3	Summarize the essence of the INPRO methodology in the area of *environmental impacts and resource depletion*, in particular: environmental effects and stressors; INPRO consideration of environmental effects; INPRO stressors basic principle; groups and limits.
4	Summarize the essence of the INPRO methodology in the area of *safety of nuclear reactor and fuel cycle*, in particular: robustness of design; realization of the defence in depth concept; human factors related to safety; necessary research, development and demonstration (RD&D) ensuring safety.
5	Summarize the essence of the INPRO methodology in the area of *proliferation resistance*, in particular: INPRO Proliferation Resistance (PR) Basic Principle; user requirements - States' commitments; attractiveness of nuclear material and technology; difficulty and detectability of diversion; multiple barriers.
6	Summarize the essence of the INPRO methodology in the area of *waste management*, in particular: radioactive waste resulting from mining and milling, conversion, enrichment, fuel manufacturing, nuclear fuel cycle facility operation, reprocessing, and decommissioning; INPRO waste management basic principle; scope and structure of INPRO assessment of NES sustainability in the area of waste management.
7	Summarize the essence of the INPRO methodology the in the area of *Infrastructure (including physical protection)*, in particular: legal framework and associated institutional arrangements needed for a successful nuclear power programme; national industrial situation; public acceptance; availability of adequate human resources and competent personnel.

No	Expected learning outcomes
8	Summarize the essence of the INPRO methodology in the area of *economics*, in particular: basic principle, user requirements and criteria; assessment of nuclear power cost and cost of alternative energy sources; the investment in nuclear power attractiveness; sensitivity of results.
9	Explain a relationship of the concept of sustainable development with the INPRO assessment methodology in the six topical areas.

I.4.5. Outline of module topics

The main topics of the module cover the following subjects.

— **Holistic approach of INPRO methodology**

Description of the relationship of the INPRO methodology with the UN concept of sustainable development to demonstrate how the INPRO methodology requirements reflect the goals of sustainable development; the INPRO assessment method and its use; an overview or summary of the INPRO methodology requirements in all six subject areas; a set of requirements, organized according to a hierarchy or architecture of basic principles, user requirements and criteria, comprising indicators and acceptance limits in all areas that must be fulfilled by an innovative nuclear energy system (INS) to meet the overall target of sustainable energy supply [6].

— **Environmental impacts (resource depletion and stressors)**

Description of interfaces of an NES with the environment and other industries; environmental impact of stressors; prerequisites for an INPRO assessment in the subject area; guidance how to apply the INPRO methodology in the area; and the corresponding user requirements [13, 14].

— **Safety (reactors and fuel cycle facilities)**

Description of approaches for safe design and operation of nuclear reactors and nuclear fuel cycle facilities (NFCFs), factors relevant to safety of reactor criticality control, radiation exposure reduction, effective containment and emergency evacuation, safety aspects in fuel front end factories, spent fuel handling and waste treatment facilities; review of safety analysis methodology (probabilistic safety assessment, probabilistic risk assessment, probabilistic and deterministic studies), understanding human and organization factors impacting safety; rules and technical criteria and codes to be followed during design; description of the role and scope of nuclear research and development organizations and their specific challenge, and the corresponding user requirements [15, 16].

— **Proliferation Resistance**

Description of national and international issues, frameworks, norms, obligations, and approaches relating to nuclear safeguards and nuclear non-proliferation as well as their practical implementation and impact on licensed nuclear facilities, and the corresponding user requirements [6, vol.5].

— **Waste Management**

Description of technologies associated with radioactive waste management including stringent controls on the releases of radioactive material (solids, liquids, airborne materials, gases) into the environment; the technological challenges and regulatory aspects associated with the end of the operating life of a nuclear or radiological facility, and the corresponding user requirements [17].

- **Infrastructure (including physical protection)**

  Description of the legal framework main aspects, the role of national industry, public acceptance of nuclear power and human resources in a nuclear power program; how to minimize the necessary nuclear infrastructure by design; and the corresponding user requirements [18].

- **Economics**

  Description of financial aspects and related risks associated with nuclear operations or projects and the importance of cost control in the effective management of budgets, scheduling and resources; and the corresponding user requirements [19].

To understand the user requirements and criteria developed by the INPRO for the six topical areas relevant to the assessment of NES, the module topics also include description and review of the basic concepts of the relevant technological processes and approaches important for use of INPRO methodology for assessing a national or global nuclear energy systems regarding their long-term sustainability.

I.4.6. Suggested teaching delivery methods and student performance assessment

Delivery of this module will be through lecturing, practical exercises, structured discussions, and self-study. Seminars and self-study assume a careful preparation for the discussions, analysis of various sources, synthesis of the material, and case studies on application of the INPRO methodology for assessing national or global nuclear energy systems regarding their long-term sustainability. The total learning hours for this module which include time for the scheduled teaching activities and self-study are estimated as sixty-four (64) hours; although, a more intensive self-study may result in increasing the learning hours.

The student performance assessment may use the following methods: short entry and exit written (preferably computerized) tests, oral questioning, and clicker activities within a conducting of teaching on module topics, observation, and evaluation of students' performance during practical exercises and discussions, and observation of attitudes exhibited.

I.4.7 Bibliography

The IAEA/INPRO methodology is in References [6, 13-19]. Additionally, the following sources are useful for teachers in developing teaching materials and for students' self-study:

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INTERNATIONAL ATOMIC ENERGY, Introduction to the Use of the INPRO methodology in Nuclear Energy System Assessment, IAEA Nuclear Energy Series No. NP-T-1.12, IAEA, Vienna (2010).

INTERNATIONAL ATOMIC ENERGY, Lessons Learned from Nuclear Energy System Assessments (NESA) using the INPRO Methodology, IAEA-TECDOC-1636, IAEA, Vienna (2009).

IAEA/INPRO e-learning course on "Analysis Support for Enhanced Nuclear Energy Sustainability" and INPRO school materials:
https://elearning.iaea.org/m2/course/index.php?categoryid=133

I.5. MODULE 5. METHODS AND TOOLS FOR SUSTAINABLE ENERGY DEVELOPMENT

I.5.1. Short description

Designing a sustainable energy system requires a comprehensive evaluation of all possible energy supply and demand options on their technical, economic, environmental, climate change and social basis. Such a comprehensive evaluation is only possible with the help of an analytical framework that allows for in-depth analysis of energy demand, evaluation of supply options, estimation of environmental impacts, valuation of financial implications, and assessment of sustainability of the alternative strategies. The IAEA has developed a set of analytical tools, called IAEA's energy models, that facilitates such an evaluation. This module introduces the IAEA's energy models [20].

The following are the main topics addressed in this module.

- Energy chains and energy system
- Approaches for developing energy scenarios
- Main drivers of energy demand
- Model for Analysis of Energy Demand (MAED)
- Assessment of energy resources and supply
- Considerations in energy supply strategies
- Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE)
- External costs of energy supply chains
- Simplified Approach for Estimating Impacts of Electricity Generation (SIMPACTS)
- Evaluating financial viability of energy projects (FINPLAN)
- Indicators for Sustainable Energy Development (ISED)

I.5.2. Learning objectives

The following are the main objectives of this module.

- Develop knowledge on the foundations for energy system modelling by introducing the systems approach to planning for sustainable energy development
- Describe the underlying methodologies of the IAEA's energy planning models
- Prepare the students to apply the models for real life applications for formulating and evaluating alternative strategies for sustainable energy development

I.5.3. Prerequisites

The students opting for this module are expected to have completed Module 1 'Energy planning and strategies for sustainable development' and preferably Module 2 'Planning for nuclear energy sustainability'.

I.5.4. Learning outcomes

After completing this module, the students are expected to have a deep understanding of conceptual and methodological foundations of energy system modelling, and have familiarization with the IAEA’s energy planning models, and acquired sufficient knowledge to further develop skills for applying the models for formulating and evaluating alternative strategies for sustainable energy development.

The students, upon completion of the module, are expected to have demonstrated the knowledge, abilities and behaviours defined in Table I.5.1.

TABLE I.5.1. LEARNING OUTCOMES UPON COMPLETION OF THE MODULE

No	Expected learning outcomes
1	Describe the conceptual and methodological foundations of energy system modelling.
2	Illustrate familiarity with the nature of energy demand and the main drivers of energy demand.
3	Review the main considerations in formulating energy supply strategies.
4	Demonstrate familiarity with external costs of energy supply chains.
5	Explain the three dimensions of sustainable energy development and indicators for gauging progress.
6	Demonstrate knowledge of the IAEA’s energy models covering the scope (including limitations), objective, data needs and results of each of the energy model.

I.5.5. Outline of module topics

The main topics of the module cover the following subjects:

— **Energy chains and energy system**

Description of various steps in extraction, conversion, transportation, distribution and final use of energy, and their interlinkage in different energy chains. Explanation of the concept of energy system, its components and boundaries, and its role in energy planning.

— **Scenario development approach**

Explanation of scenario development approaches for long term energy planning, and description of methodologies for scenario development to ensure internal consistency, plausibility, and transparency.

— **Main drivers of energy demand**

Description of the nature of energy demand in an energy system and the main drivers of energy demand, such as demographic changes, economic progress, technological development, social trends, and other relevant factors.

— **Model for Analysis of Energy Demand (MAED)**

Introduction of IAEA’s energy demand model MAED. Description of MEAD’s methodological approach, scope and coverage of the model, its input data requirements and the results. Explanation of scenario development approach for assessment of future energy demand.

- **Assessment of energy resource and supply potential**

  Description of categorization of fossil fuel resources (proven reserves, inferred and estimated resources), and renewable energy sources. Explanation of methodologies for estimating future supply potential of the various energy resources/sources, and for assessing the technical limitations and the cost of extraction.

- **Considerations in energy supply strategies**

  Description of technical, economic, environmental and climate change aspects of the various energy options for formulating alternative energy strategies. Explanation of main considerations, e.g., energy accessibility, affordability, reliability, security, environmental and climate change, for developing sustainable energy systems and their compatibility with overall sustainable development.

- **Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE)**

  Introduction of IAEA's energy supply model MESSAGE, description of its methodological approach, scope and coverage of the model, its input data requirements and the results. Description of approaches for policy and strategy formulation with the help of MESSAGE.

- **External costs of energy supply chains**

  Explanation of the concept of external costs of energy supply and use. Review of a comparison of various energy chains in terms of their damage to public health, ecological systems, infrastructure and other external costs.

- **Simplified Approach for Estimating Impacts of Electricity Generation (SIMPACTS)**

  Introduction of IAEA's model SIMPACTS, description of its methodological approach, scope and coverage of the model, its input data requirements and the results. Explanation of model results for estimating impacts on public health and environmental damage costs for ranking various energy options.

- **Evaluating financial viability of energy projects (FINPLAN)**

  Introduction of IAEA's model FINPLAN, description of its methodological approach, scope and coverage of the model, its input data requirements and the results. Explanation of model results evaluating the financial viability for choosing various energy options.

- **Indicators for Sustainable Energy Development (ISED)**

  Description of the concept of indicators for gauging progress on sustainable energy development. Introduction of IAEA's framework ISED covering social, economic and environmental dimensions, and description of statistics and data needed for constructing energy indicators; and explanation of approaches for using ISED for comparing alternative energy strategies in terms of their compatibility with sustainable development.

I.5.6. Suggested teaching delivery methods and student performance assessment

Delivery of this module will be through lecturing, demonstrations, exercises, and self-study. Seminars and presentation of country case studies can elaborate the usefulness of the energy models. The total learning hours for this module which include time for the scheduled teaching activities and self-study are estimated as thirty-two (32) hours; although, a more intensive self-study may result in increasing the learning hours.

The student performance assessment can be done with the help of quizzes and evaluation of students' performance during case study exercises.

I.5.7. Bibliography

INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Tools and Methodologies for Energy System Planning and Nuclear Energy System Assessments, Department of Nuclear Energy, IAEA Brochure, IAEA, Vienna (2009).

BENNETT, L.L., MOLINA, P.E., MUELLER, T., "Energy and nuclear power planning studies", IAEA Bulletin 3/1990, IAEA, Vienna (1990).

INTERNATIONAL ATOMIC ENERGY AGENCY, Energy and nuclear power planning study for Pakistan (covering the period 1993-2023), IAEA-TECDOC-1030, IAEA, Vienna (1998).

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INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Modelling Tools for National Energy & Climate Plans (NECPs), IAEA, Vienna, March 2019. https://energy-community.org/dam/jcr:a05502f3-6da0-4fc0-bc12-0216a8d1e822/Climate_WS-IAEA_032019.pdf

INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Features its Energy Planning Tools at Global SDG7 Conference, IAEA Department of Nuclear Energy, February 2018. https://www.iaea.org/newscenter/news/iaea-features-its-energy-planning-tools-at-global-sdg7-conference

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I.6. MODULE 6. METHODS AND TOOLS FOR MODELLING AND ANALYSIS OF NUCLEAR ENERGY SYSTEMS

I.6.1. Short description

This module addresses the INPRO approaches and tools for NES scenario analysis and modelling, comparative evaluation of NES options and NES economic analysis. More specifically, the module covers: (a) IAEA INPRO framework for NES scenario analysis and modelling including representation of the architecture of a NES; (b) IAEA INPRO approach for comparative evaluation of NES/scenario options and KIND-ET tool for NES comparative analysis; (c) Nuclear Economics Support Tool (NEST) which provides evaluation of levelized unit electricity cost and figures of merit for NPPs with different nuclear reactors on plant level and analyses its sensitivity to various factors and advance uncertainty analysis.

The following are the main topics addressed in this module.

- Introduction to INPRO approaches and tools for modelling and analysis of nuclear energy systems [29]
- INPRO framework for NES scenario modelling and analysis [21, 22, 24, 25]
- Basics for NES mass flow and economic analysis [21]
- NES Simulators - simple models of a nuclear energy system
- Modelling of nuclear energy systems with MESSAGE-NES [26, 27]
- NES road mapping and ROADMAPS-ET [28]
- Multi-criteria decision making for judgment aggregation [31]
- Comparative evaluation of NES options with the use of multiple-criteria decision analysis (MCDA): the KIND approach and tool [31]
- NESA Economics Support Tool (NEST)

I.6.2. Learning objectives

The following are the main objectives of this module.

- Familiarize the students with the approaches for modelling and analysis of nuclear energy systems as developed by INPRO.
- Explain the basis for mass flow analysis and multi-criteria decision making for judgment aggregation.
- Familiarize the students with the INPRO approach for comparative evaluation of nuclear energy options and scenarios.
- Describe the INPRO approach for NES road mapping;
- Introduce INPRO tools for NES scenario analysis, comparative evaluation of NES options and NES economic analysis.

I.6.3. Prerequisites

The students are expected to fulfil the following prerequisites for entering this module.

- Possess a basic mathematics educational background and knowledge of the nuclear physics and technology basics.
- Basic knowledge of Microsoft Excel software.
- The module covers different nuclear areas and considers nuclear power as a system, and addresses many of its aspects including specialized knowledge in a number of

mathematics, mathematical modelling and nuclear fields. Some specialized prerequisite knowledge is advantageous but not mandatory, e.g., knowledge in linear programming, multi-criteria decision analysis, probability theory, fundamentals of energy planning and economics of nuclear energy, reactor physics, neutron physics, radioecology and radioactive waste management, infrastructure (including legal aspects) of nuclear power programmes, and programming basics. The mentioned specialized knowledge, if necessary, can be acquired by the students within the module, depending on the audience.

— Successfully complete a core module 2 'Planning for Nuclear Energy Sustainability' of the model curriculum; and optionally a core module 1 'Energy planning and strategies for sustainable development' and an advanced module 5 'Methods and Tools for planning sustainable energy development'.

I.6.4. Learning outcomes

The module contributes to competency areas belonging to the following groups: Group 2 'Planning for nuclear energy sustainability'; Group 3 'Innovations in nuclear energy sector in meeting sustainable energy development challenges'; Group 4 'Nuclear energy systems modelling and analysis'; and Group 5 'The methodology for assessing the sustainability of nuclear energy systems (the INPRO Methodology)'.

The students, upon completion of the module, are expected to have demonstrated the knowledge, abilities and behaviours defined in Table I.6.1.

TABLE I.6.1. LEARNING OUTCOMES UPON COMPLETION OF THE MODULE

No	Expected learning outcomes
1	Describe the INPRO approaches to modelling and analysing nuclear energy system.
2	Using the module teaching materials, describe the framework for modelling and analysis of NES scenarios and main elements of the framework.
3	Perform exercises on dynamic NES modelling using NES simulators and economic analysis at NPP level with NEST tool.
4	Illustrate familiarity with MESSAGE-NES for modelling nuclear energy scenarios.
5	Illustrate familiarity with presenting nuclear development plans with ROADMAPS-ET.
6	Demonstrate knowledge of approaches and tools for NES comparative evaluation considering various key factors and multi-criteria analysis methods to select the preferred nuclear energy system.
7	Perform exercises on NES comparative evaluation using the IAEA tool KIND-ET and its extension.
8	Based on application of the INPRO tools and approaches to the case studies, formulate the main challenges for sustainable nuclear energy development and deployment, the role of innovation and international cooperation in long term sustainability of nuclear energy, and strategic planning for the NES deployment.

I.6.5. Outline of module topics

The main topics of the module cover the following subjects:

— **Introduction to INPRO approaches and tools for modelling and analysis of nuclear energy systems**

Overall information on INPRO approaches and tools for modelling and analysis of nuclear energy systems, including: (1) modelling of nuclear energy evolution scenarios, and MESSAGE-NES and ROADMAPS tools; (2) economic evaluation of nuclear energy systems and NESA Economics Support Tool (NEST); (3) comparative evaluation of NES or scenario alternatives and KIND-ET tool, databases, and information sources.

— **INPRO framework for NES scenario modelling and analysis**

IAEA INPRO framework for nuclear energy scenario evaluation including nuclear demand for NES, a heterogeneous world model, metrics based on a set of scenario-specific key indicators in the areas of mass flows, resources, wastes, demands for the front-end and back-end fuel cycle services, tools to evaluate scenarios of a dynamic nuclear energy system, data collection for material flow and economic analysis of complex NES and sample scenario studies.

— **Basics for NES mass flow and economic analyses**

Mass flow and economic analysis for once-through fuel cycle based on thermal reactors and closed fuel cycle with plutonium multi-recycling based on thermal and fast reactors; annual and cumulative requirements for fuel cycle products and services including the requirements for natural uranium mining and milling, conversion, enrichment, fuel production, spent fuel storage and reprocessing services, and nuclear reactor commissioning and decommissioning schedules.

— **NES Simulators – simulators for scenario analysis of NESs**

Description of six simulators of nuclear energy systems for conducting mass flow and economic analyses. These simulators are based on simplified approachesand include: (1) a nuclear energy system based on a thermal reactor in a once-through fuel cycle; (2) a nuclear energy system based on light- and heavy-water reactors (LWR and HWR) in a once-through fuel cycle; (3) a nuclear energy system based on light-water thermal reactors with UOX and MOX fuel in a partially closed fuel cycle; (4) a nuclear energy system based on light-water thermal reactors and fast reactors (LWR and FR) in a closed fuel cycle; (5) a reactor unit deployment economic simulator for cash flow modelling and evaluation of economic performance metrics; (6) nuclear fuel depletion and burn-up model. The simulators evaluate annual and cumulative needs for fuel cycle products and services, both for front- and back-end as well as the economic performance of the nuclear power programme.

— **Modelling of nuclear energy systems with MESSAGE-NES**

Information on extension of MESSAGE capabilities for modelling of complex NES including specific technical and economic aspects of NES to support sustainability evaluation of different nuclear options. Three MESSAGE demo cases are considered: NES based on thermal reactors with once-through fuel cycle; NES based on thermal reactors with reprocessing to feed plutonium as mixed oxide (MOX) fuel; NES based on thermal and fast reactors with a fully closed fuel cycle. The main outputs of modelling with MESSAGE-NES include an optimized deployment plan for various nuclear technologies including details of the sizes and timings for building various facilities, NFC service requirements, material mass flows, nuclear material inventories, resource depletion, accumulated radioactive wastes, and investment and operating costs. Application of MESSAGE-NES to global and national case studies.

— **NES road mapping and ROADMAPS-ET**

Introduction to road mapping process and description of the major outputs of the INPRO collaborative project ROADMAPS, which integrates the results of Global Architecture of Innovative Nuclear Energy Systems based on Thermal and Fast Reactors including a Closed Fuel Cycle (GAINS), Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES) and some other INPRO collaborative projects into the roadmap template for structured approach for globally enhancing nuclear energy sustainability. ROADMAPS tool (a Microsoft Excel spreadsheet) based on the ROADMAPS template to support the practical application of the abovementioned approach, and the analysis and visualization of the results of such applications. Examples of a trial application of the ROADMAPS template and the integration approach in a series of case studies performed by project participants.

— **Multi-criteria decision making for judgment aggregation**

General description of NES evaluation studies and background of decision-making process and details of MCDA methods such as value based, outranking, and reference based. Structured framework to determine preferred alternative, including: problem formulation and establishment of goals; identification of indicators; formulation of alternatives (NES options); selection and application of MCDA method; determination of alternative ranking, and sensitivity and uncertainty analysis; final conclusion and recommendations.

— **Comparative evaluation of NES options with the use of multiple-criteria decision analysis (MCDA): the KIND approach and tool**

Approach and tool developed within the INPRO collaborative project KIND for comparative evaluation of innovative and evolutionary nuclear energy system options / nuclear energy evolution scenarios regarding sustainability. Multi-attribute value theory (MAVT) and sensitivity / uncertainty analysis methods, and a set of specially developed recommendations for performing case studies on NES comparison. The KIND tool based on the KIND approach for the performance of comparative evaluations of nuclear energy system options, and the application of the KIND approach and KIND tool for global and national case studies.

— **NESA Economics Support Tool (NEST)**

Description of Nuclear Energy System Assessment Economics Support Tool (NEST) to support NES sustainability assessments and NES scenario analysis. NEST inputs including technical and economic data for different type of reactors and associated fuel cycles. NEST output including a set of economic indicators including levelized unit energy cost (LUEC), net present value (NPV), internal rate of return (IRR), return on investment (ROI), sensitivity and uncertainty analysis.

I.6.6. Suggested teaching delivery methods and student performance assessment

Delivery of this module will be through lecturing, practical exercises and self-study, totally about 70 hours, equally distributed. However, a more intensive self-study may result in increasing the learning hours.

The assessment of learning and student performance for this module will be through tests, and oral questioning and clicker activities during teaching on particular topics, observation and evaluation of students' performance during practical exercises and discussions, written reports and oral presentations.

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I.7. MODULE 7. RESEARCH PROJECTS ON PLANNING AND ASSESSMENT OF ENERGY AND NUCLEAR ENERGY SYSTEMS

I.7.1. Short description

The module involves the fulfilment of research projects on planning and assessment of overall energy systems and, in particular, nuclear energy systems, in selected topical areas relevant to strategic planning for the sustainable nuclear energy development, which can be carried out as part of the curriculum.

I.7.2. Learning objectives

The main objectives of this module are:

- to develop knowledge and skills in applying the IAEA energy planning models to explore sustainable energy strategies;
- to develop abilities in applying approaches and tools used in modelling and analysis of nuclear energy systems;
- to support in acquiring practical skills in the development of scenarios and conducting of economic and comparative assessments of alternative nuclear energy systems.

I.7.3. Prerequisites

The students performing projects proposed in this module are expected to have completed Modules 1, 2, 4, 5 or 6, and preferably Module 3 of the model curriculum.

I.7.4. Learning outcomes

The students, upon completion of projects proposed in this module, are expected to have demonstrated the knowledge, abilities and behaviours defined in Table I.7.1. Particular outcomes achieved by the student depend on the specific project or projects performed by the student.

TABLE I.7.1. LEARNING OUTCOMES UPON COMPLETION OF THE MODULE

No	Expected learning outcomes
1	Explore examples of modelling scenarios for developing national, regional and global nuclear energy systems (NES).
2	Analyse examples of performed modelling studies and assessments of the NES development.
3	Report on the application of selected INPRO/IAEA scenario modelling tools, using examples
4	Analyse innovative NES options considered by the INPRO, based on modelling results.
5	Apply INPRO approaches and tools to planning and analysing of the overall development of the energy system and, in particular, the development of NES.
6	Judge the fulfilment of INPRO methodology criteria applying the INPRO methodology for sustainability assessment of NES.
7	Appraise the issues of sustainable NES development.
8	Summarize the need for the development of NES in accordance with the United Nations concept of Sustainable Development.
9	Propose a national or regional NES development study, composing a related scenario.
10	Identify potential future technological and institutional developments to achieve sustainability of nuclear energy systems.
11	Employ - in a reasonable and justified manner - the foresights for the potential technological and institutional innovations in nuclear energy.
12	Propose a solution for the development and improvement of NES' components to achieve the INPRO methodology criteria for sustainability of NES, identifying gaps, and drawing and prioritizing a list of required research and development (R&D) to close gaps.

I.7.5. Outline of project topics

The topics of the projects can be based on the palette of all the topics addressed in the core and advanced modules of the model curriculum, and — what is important — corresponding to the national needs and meeting the expectations of particular educational organizations (including universities). Below are examples of project topics and tasks within the projects.

I.7.5.1. Overall energy scenarios

Scenario analysis and examining based on application of IAEA tools

- Apply IAEA tools to carry out scenario analyses for development of sustainable energy systems.
- Perform the analysis of structural changes to energy demand in the given country to combat climate change considering technical, economic and social constraints and limitations (using the IAEA's Model for Analysis of Energy Demand MAED).
- Formulate and evaluate energy supply strategies for sustainable energy development for the given country (using the IAEA's Model for Energy Supply Strategy Alternatives and their General Environmental Impacts MESSAGE).
- Compare alternative energy scenarios using indicators for sustainable energy development.
- Evaluate cost-effectiveness of nuclear power for mitigating future greenhouse gas (GHG) emissions in the given country (using the IAEA's model MESSAGE and Nuclear Economics Support Tool NEST).
- Evaluate the potential for non-power applications of nuclear energy in the given country (using the IAEA's model MESSAGE).

I.7.5.2. Nuclear energy scenarios and NES options

Nuclear energy scenario modelling and analysis based on application of the IAEA INPRO tools

- Explore global deployment scenarios for NES with thermal and fast reactors based on the INPRO toolkit (including tools NEST, MESSAGE-NES, KIND-ET, ROADMAPS-ET).
- Explore scenarios for global deployment of NES with minor actinide transmutation based on the INPRO toolkit (including tools MESSAGE-NES, KIND-ET).
- Explore global and regional NES scenarios with the introduction of thorium based on the INPRO toolkit (including tools MESSAGE-NES, KIND-ET).
- Perform comparative multi-criteria evaluations and ranking of NES options according to selected key indicators of INPRO methodology criteria for NES sustainability (using the approach developed within the INPRO collaborative project KIND and the KIND-ET tool).
- Compare the economic competitiveness of nuclear power at the plant level and at the electric system level (using tools MESSAGE-NES and NEST).
- Optimize the structure of the NES, considering the multiple resource and infrastructure constraints (using the MESSAGE-NES tool).
- Perform comparative evaluation of electricity costs according to different investment schedules for the given NES and alternative NESs. Assess the levelized unit energy cost (LUEC) (including its components) for NPPs with different nuclear reactors and analyse its sensitivity to various factors (using the NEST tool).
- Carry out mass flow and economic analysis, considering the multiple resource and infrastructure constraints (using NES Simulators and the MESSAGE-NES tool).
- Develop roadmaps for specific NES deployment scenarios tracking progress against key milestones (using results of the INPRO collaborative project ROADMAPS and ROADMAPS-ET tool).
- Design a scenario and make a proposal for a national or regional study of NES development (using tools NEST, MESSAGE-NES, KIND-ET, ROADMAPS-ET).
- Evaluate the role of innovations for improvements in economics, use of natural resources, proliferation resistance, waste management and infrastructure (using tools NEST, MESSAGE-NES, KIND-ET, ROADMAPS-ET).

I.7.5.3. NES assessment

Limited scope NES assessment according to the INPRO Methodology

(This project is intended for a group activity.)

- Perform a limited scope assessment of the selected NES in one or more INPRO methodology topical areas in accordance with the latest edition of the manual on the application of the INPRO Methodology for a holistic NES assessment.
  (For example, the following assessment areas may be chosen: economics, infrastructure, waste management, proliferation resistance.)
- Describe the role of innovations to improve the NES' components and specific attributes to achieve the INPRO methodology criteria for sustainability of NES.

I.7.6. Suggested teaching delivery methods and student performance assessment

Organizational frameworks for this module can be diverse, such as: coursework, an assignment within a particular module, or work during internship, and/or a master's thesis. In each case the learning outcomes should be reviewed and adjusted accordingly. An assumption is students will have access to the IAEA tools for planning and assessing energy and NES.

Projects that encourage students to make decisions about which direction to go and work independently are common in the university studies. Projects take many forms. Students may complete small projects as an assignment in a module, either on their own or collectively with classmates. As a useful way of learning, students may perform small project activities. On the other hand, a master's or doctoral thesis in a field of research, such as a Ph.D., is a large project that — in the case of a doctoral degree — takes several years to complete. This should make students experts in their chosen area of specialization.

The master's thesis plays a central role in the master's program. This is the most important part of the master's study. This is a proof of the student's skill and academic development at sufficient level. Successful fulfilment of the thesis is a basis for taking decision that the graduate is qualified. It also ensures that the final master achievement levels have been reached.

The master's thesis provides essential training. With regard to the educational programmes employing the model curriculum, the master's thesis involves many academic activities associated with the IAEA methods and tools for planning sustainable energy development and INPRO approaches to modelling and analysis of NES: formulating the research objective and a research question; sorting, interpretation, and synthesis of information; application of IAEA (including INPRO) tools for a specific case or task; collection and analysis of data/observations; preparation and presentation of oral or written reports on the results.

Teachers should provide a clear statement of the task, parameters, and resources the students can use to proceed with their project work, that include goals and objectives; description of the task; as applicable to particular projects, model description, input data, NES options; assumptions and metrics for analysis or scenario evaluation; expectations for the analysis and presentation of results; resources to be used including references, bibliography and software tools; training on the use of software tools, if needed; and criteria for project assessment.

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APPENDIX II. DESCRIPTION OF THE IAEA TOOLS

II.1. ANALYTICAL TOOLS TO SUPPORT ENERGY SYSTEM ANALYSIS AND PLANNING

The IAEA developed a set of computer-based energy models which provide a consistent framework for formulating long-term energy strategies and evaluating the potential role of various energy options, including nuclear energy, and for designing sustainable energy systems. A short description of these models is given below.

The Model for Analysis of Energy Demand (MAED) evaluates future energy demand based on a set of consistent assumptions on medium- to long-term socioeconomic, technological, and demographic developments in a country or a region. Future energy needs are linked to the production and consumption of goods and services; technology and infrastructure innovation; lifestyle changes caused by increasing personal incomes; and mobility needs. Energy demand is computed for a host of end use activities in three main 'demand sectors': household, services, and industry and transport. MAED provides a systematic framework for mapping trends and anticipating change in energy needs, particularly, as these correspond to alternative scenarios for socioeconomic development.

The Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) combines technologies and fuels to construct so-called 'energy chains', making it possible to map energy flows from resource extraction, beneficiation and energy conversion (supply side) to the distribution and the provision of energy services (demand side). The model can help design long-term energy supply strategies or test energy policy options by analysing cost optimal energy mixes, investment needs and other costs for new infrastructure, energy supply security, energy resource utilization, rate of introduction of new technologies (technology learning), and environmental constraints.

The Wien Automatic System Planning Package (WASP) is an effective tool for power planning in developing countries. It helps to determine 'optimal' expansion plans for power generation within constraints identified by local analysts, which may include – among others – limited fuel availability, emission restrictions and system reliability requirements. WASP explores all possible sequences of capacity additions that are capable of satisfying demand while also meeting system reliability requirements. It accounts for all costs associated with existing and new generation facilities, reserve capacity and un-served electricity.

The Model for Financial Analysis of Electric Sector Expansion Plans (FINPLAN) is used for financial analysis of electricity generation projects by considering financing sources, expenditures, revenues, taxes, interest rates and weighted average capital costs, and other factors. Since financial constraints are often the biggest obstacle to implementing an optimal energy strategy, the model is particularly helpful for exploring the long-term financial viability of projects by preparing cash flows, income statements, balance sheets and financial ratios.

The Simplified Approach for Estimating Impacts of Electricity Generation (SIMPACTS) estimates and quantifies health and environmental damage costs, so-called 'externalities', of different electricity generation technologies. This tool is particularly useful for comparative analyses of fossil, nuclear and renewable electricity generation, siting of new power plants, or cost-effectiveness of environmental mitigation policies. A key strength of SIMPACTS is that it already delivers useful results when only limited data are available.

The Indicators for Sustainable Energy Development (ISED) framework provides a flexible tool for analysts and decision makers to better understand their national energy situations and trends, and the impacts of policies and Solar energy – a renewable option – policy changes on the energy system. The indicators reflect the interaction of energy with the economic, social and environmental aspects of sustainable development over time. The ISED can also be used to monitor progress of policies and strategies for sustainable energy development.

II.2. ANALYTICAL TOOLS TO SUPPORT NUCLEAR ENERGY MODELLING AND ANALYSIS

The IAEA INPRO has produced a set of analytical tools to help design strategies for the development of a sustainable nuclear energy programme. These tools support evaluation of various nuclear energy technologies in terms of their economic competitiveness, natural resource use, waste generation, environmental impacts, required safety and needed infrastructure, proliferation resistance, public acceptance, and other factors. These analytical tools are briefly described below.

NEST (NESA Economic Support Tool)

NESA Economics Support Tool was developed by INPRO to perform economic analysis and assessment of nuclear energy systems. It uses the cost economics concepts and addresses specific details of the nuclear energy system. NEST requires basic technical and economic parameters of nuclear power reactors and their fuel cycle as inputs. The technical parameters include reactor power output, load factor, lifetime, fuel burnup, and other parameters. The economic parameters are investment cost, construction schedule, nuclear fuel cycle (NFC) services cost, operation and maintenance (O&M) cost, discount rate, and other parameters. Using these inputs, NEST calculates Levelized Unit Energy Cost and other figures of merit, like net present value (NPV), internal rate of return (IRR) and return on investment (ROI). NEST is capable to carry out a sensitivity/uncertainty analysis for levelized unit energy cost (LUEC) or its components caused by the uncertainties of input parameters.

MESSAGE-NES

An adapted and enhanced version of MESSAGE that is the main IAEA tool for supporting nuclear power planning studies (scenario and material flow analyses). MESSAGE-NES provides a convenient platform for modelling complex nuclear energy systems and developing alternative scenarios of the system dynamic evolution, including material flow analyses and evaluations of trade-offs between various nuclear energy system (NES) sustainability aspects. Modelling an NES is quite flexible in MESSAGE, and users can decide which components to include in the model. Each component can be represented in MESSAGE with necessary details, such as first loading and final unloading of fuel in reactors, cooling time for spent fuel discharged from the reactor, lag and lead time for processes, and losses. Nuclear power processes can be taken into account such as changes in the isotopic composition of spent fuel during the cooling time in storage at the nuclear power plant (NPP) or reprocessing lag time due to the radioactive decay of unstable isotopes. Nonetheless, MESSAGE has some limitations with regard to taking account of the decay of plutonium and minor actinides in intermediate stocks.

KIND-ET

KIND Evaluation Tool (KIND-ET) is an Excel-template based on the multi-attribute value theory (MAVT) for comparison and ranking of nuclear energy systems / evolution scenarios. KIND-ET covers most of the formal stages of the decision support process. Before performing a multi-criteria comparative evaluation of NES / scenarios using the KIND-ET tool, users preliminary need to specify alternative NES / scenarios, identify and evaluate key indicators, and identify a structure of the objective tree including high-level objectives, evaluation areas, indicators and their hierarchical interrelation. KIND-ET evaluates overall ranks of NES options, taking into account the NES performance, as well as experts' and decision makers' judgments and preferences. For an advanced uncertainty / sensitivity analysis in regard to weights, key indicators and single-attribute value functions, supplementary modules were developed. They can be used independently or in any combination to deepen the analysis / expertise and enhance the quality of represented results. Domination Identifier module is designed for identification of non-dominated and dominated options among the set of considered alternatives. Overall Score Spread Builder is an express tool for evaluation of option overall score spreads caused by uncertainties in weighting factors and the objectives tree structure. Ranks Mapping Tool provides a visualization to highlight the options taking the first rank for different combinations of high-level objective weights. Uncertainty Propagator is an instrument based on the traditional error analysis framework for evaluating uncertainties in options' overall scores due to uncertainties in single-attribute value function forms and key indicators. KIND-ET provides different types of visualization such as value paths, radar chart, bar chart, and pie chart for results interpretation. NES ranking results have a clearer and meaningful interpretation by decomposing the overall score into individual area / key indicator (KI) contributions in accordance with the structure of the objectives tree.

ROADMAPS-ET

ROADMAPS-ET is a flexible and universal Excel based tool designed for the analysis and presentation of analytical results regarding NES deployment strategies for enhancing sustainability at a national, regional or global level. ROADMAPS-ET can be used for strategic planning, analytical studies, the preparation of reporting documentation for management and summaries for the media regarding issues related to enhancing NES sustainability.

ROADMAPS-ET tool incorporates recent methodological achievements and best practices in the area of the development and presentation of national nuclear energy roadmaps for enhancing nuclear energy sustainability. It provides for:

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

The ROADMAPS-ET tool is not a computational code but an analytical decision support tool for structuring and unifying data on issues related to NES sustainability enhancement using the Gantt charts. ROADMAPS-ET comprises twenty sheets in an Excel workbook for specifying various elements of a roadmap. The tool combines all these elements, following technical and practical logic, to help experts and decision makers understand the main issues related to enhancing the sustainability of nuclear energy. The outputs are visualized by means of the Gantt charts showing key developments on a timeline and an implementation schedule of action items. Nuclear fuel cycle material flow information for the existing and future reactors and the associated fuel cycle front end and back end is included.

Nuclear energy system simulators (NES simulators)

These simulators were developed by INPRO for conducting mass flow and economic analysis of dynamic nuclear energy system to support INPRO outreach activities. NES simulators are important for understanding and using more sophisticated INPRO tools, such as MESSAGE and NEST. Simulators comprise six models:

Model 1: Simple model of a nuclear energy system based on a thermal reactor in a once-through fuel cycle. This is a model of a nuclear energy system (NES) based on a thermal reactor in a once-through fuel cycle. The model evaluates annual and cumulative fresh and spent fuel flows as well as economic performance of the nuclear power programme.

Model 2: NES based on LWRs and HWRs in a once-through fuel cycle

This is a model of a NES based on the light- and heavy-water thermal reactors (LWRs and HWRs) in a once-through fuel cycle. The model specifies both fuel cycle front-end and back-end details. It is assumed that LWR and HWR spent fuel is moved to the at-reactor pools for cooling, then it goes to the away-from-reactor storage facilities and after that to the geological repositories.

Model 3: NES based on light-water thermal reactors with UOX and MOX fuel in a partially closed fuel cycle

This is a model of a NES based on the thermal reactors utilising UOX and MOX fuel in a partially closed fuel cycle with a single plutonium recycle. The simulator specifies both fuel cycle front-end and back-end details. Only UOX spent fuel can be reprocessed. Arising of HLW during spent fuel reprocessing is directed to geological disposal.

Model 4: NES based on light-water thermal reactors and fast reactors in a closed fuel cycle

The model is based on light-water thermal reactors and fast reactors (LWRs and FRs) in a closed fuel cycle. The model specifies both fuel cycle front-end and back-end details.

Model 5: The reactor unit deployment economic simulator is an easy-to-use software tool which can enable nuclear planning experts to perform a simplified cash flow modelling and evaluation of economic performance metrics for scenarios of serial deployment of the identical reactor units. The model evaluates total discounted cost, net present value, internal rate of return, payback period, return on investment and levelised unit energy cost including its structure.

odel 6: Nuclear fuel depletion and burnup simulator is the ease-to-use isotopic and burnup simulator which can enable nuclear planning experts to assist nuclear energy system modelling and scenario analysis studies as a part of material flow and economics analyses. Reactor and fuel cycle types: the current version is applicable for the consideration of isotopic and burnup issues for different reactor types in the uranium and uranium-plutonium fuel cycles.

NFCSS Nuclear Fuel Cycle Simulation System

The Nuclear Fuel Cycle Simulation System (NFCSS) is a scenario-based computer simulation tool that can model various nuclear fuel cycle options in various types of nuclear reactors. The NFCSS allows users to efficiently and accurately identify the nuclear mineral resources and technical infrastructure needed for the front end of the nuclear fuel cycle; the amounts of used fuel, actinide nuclides and high-level waste generated for a given reactor fleet size; and the impact of introducing recycling of used fuel on mineral resource savings and waste minimization. A simplified fuel depletion module called Calculation of Actinide Inventory

estimates of various material accumulations from nuclear reactor operation. The CAIN requires a small number of input parameters and gives results in a very short time. The NFCSS has been used for carrying-out fuel cycle assessments for two main commercial nuclear fuels, namely, UO2 fuel and Pu-doped uranium dioxide (MOX) fuel, and for NPPs with five types of reactors that mostly compose the global nuclear reactor fleet, i.e. pressurized light water moderated and cooled reactors PWRs and VVERs, boiling light water moderated and cooled reactors BWRs, pressurized heavy water moderated and cooled reactors PHWRs, light water cooled graphite moderated reactors RBMKs, gas cooled graphite moderated reactors AGRs and GCRs. There are currently seven reactors selectable at the NFCSS basic calculation web site: PWR, BWR, PHWR, RBMK, AGR, GCR and VVER. Recently, the NFCSS has been extended for application to thorium fuel cycles for light water moderated and cooled reactors (LWRs). It also has been demonstrated that in principle the NFCSS is capable of modelling fuel cycles of fast reactors (FRs). The NFCSS can calculate the actinide inventory such as uranium (U), plutonium (Pu), minor actinides (MAs) (e.g. Np, Am and Cm) entrained in spent fuels using the CAIN fuel depletion model. For a given nuclear programme size, the NFCSS can provide estimates of material flows and various fuel cycle requirements such as natural uranium resources, enrichment services in separative work unit (SWU), volume of fuel fabrication, volume of spent fuels, accumulation of Pu and MAs, reprocessing volumes and so on.

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ANNEX I. INPRO AND UN SUSTAINABILITY CONCEPT

See the separate file.

GLOSSARY

assessment (INPRO assessment of NES sustainability). An assessment using the INPRO methodology is a process of making a judgment about the long-term sustainability of a nuclear energy system. In principle, analyses using analytical tools are not part of an INPRO assessment but could provide necessary input for the assessment. The assessment of a nuclear energy system is done at the criterion level of the INPRO methodology. In the case of a numerical criterion, the assessment process consists of comparing the value of an indicator with the value of the acceptance limit of a criterion. In the case of a logical criterion – mostly phrased in the form of a question – the assessment is done by answering the question raised.

basic principle (BP). As defined in the INPRO methodology, an INPRO basic principle is a statement of a general goal that has to be achieved in order to make a nuclear energy system sustainable in the long term. It therefore provides a basic impetus for the development of necessary capabilities and design features.

competence (competency). A combination of knowledge, skills and attitudes in a particular field, which, when acquired, allows a person to perform a job or task to identified standards. Competence (competency) may be developed through a combination of education, experience and training. A term 'competency' is also used for a generic task or a function (e.g. for nuclear facility manager jobs).

course. A part of an educational or training programme addressing a particular area or group of topics. A course consists of several modules.

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

curriculum. A set of subject areas covered within a specified programme of study.

dynamic NES. A model of nuclear energy systems that allows performing time-dependent material flow analysis, assessment of environmental impact, economic competitiveness and socio-political analysis for time-evolving nuclear energy systems. Dynamic models take into account possible dynamical mass flow feedback effects becoming become complex when symbiotic flows among reactor types are to be modelled (e.g., temporary building up separated fissile/fertile material inventories during transition periods).

embarking country. A country intending to begin a nuclear power programme.

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

innovative design. This is an advanced nuclear installation design that incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. These reactors may comprise not only electricity generating plants but also include also plants of various size and capacity for other applications, such as high-temperature heat production, district heating and sea water desalination, to be deployed in developed regions as well as in developing countries and countries in transition. Examples of innovative reactors are Generation IV reactors.

innovative nuclear energy systems (INS). INS in INPRO, encompasses all systems that will position nuclear energy to make a major contribution to global energy supply in the 21st century. In this context, future systems and thus, INPRO, may include evolutionary as well as innovative designs of nuclear facilities.

INPRO framework. A framework which provides a sound basis for structuring relevant data characterizing the performance of nuclear energy deployment scenarios and comprises the following steps: nuclear demand for NES, architectures of NES, fuel cycle schemes, metrics for scenario analysis, reactor and fuel data, scenario assumptions, tools for NES modelling, and framework applications.

key indicator. A specific, usually measurable, indicator showing how a system performs in a particular area. They have a distinctive capability for capturing the essence of a given area and provide a means to establish targets in a specific area to be reached via improving technical or infrastructural characteristics of the NES.

KIND approach. A set of actions intended to deal with comparative evaluations of NES options based on the selection and use of a limited number of key indicators along with the state-of-the-art judgment aggregation and sensitivity/uncertainty analysis methods.

KIND-ET (KIND-evaluation tool). Multi-attribute value theory (MAVT) based Excel toolkit for the INPRO Collaborative Project 'Key Indicators for Innovative Nuclear Energy Systems' developed for the multi-criteria comparative evaluation of NES options in accordance with the approach and recommendations elaborated in the KIND project.

learning objective. A very general statement about the larger goals of the course or programme.

learning outcome. A very specific statement that describes exactly what a student will be able to do in some measurable way.

levelized unit energy cost (LUEC). The price that would have to be charged per unit of production, e.g., $ per kW·h over the assumed lifetime of the plant to recover all costs, including investment costs, operating and maintenance costs, fuel costs and all other relevant costs and/or allowances, such as decommissioning and disposal costs.

master's degree. An academic degree granted to individuals who have undergone study demonstrating a mastery or high order overview of a specific field of study or area of professional practice. The master's course takes place beyond the bachelor's degree. It generally lasts two years but can range from one to three years depending on the national educational system.

MESSAGE (model for energy supply strategy alternatives and their general environmental impacts). A modelling framework for medium- to long-term energy system planning, energy policy analysis, and scenario development.

MESSAGE-NES. An adaptation of MESSAGE tool for supporting nuclear power planning studies for scenario and material flow analyses.

mixed oxide (MOX) fuel. Nuclear reactor fuel, which is comprised of a mixture of plutonium oxide (usually about 5% Pu) and uranium oxide.

module. A self-contained instructional unit that is designed to satisfy one or more learning objectives and to achieve the defined learning outcomes.

multi-attribute value theory (MAVT). A value-based MCDA method assuming judgement aggregation in terms of measured/evaluated costs, risks and benefits into an overall score using single-attribute value functions taking into account the experts and decision-maker preference strength.

multi-criteria decision analysis (MCDA). An area of multiple criteria decision-making in which to a number of the alternative decision choices are explicitly pre-specified: each option is represented by its performance indicators evaluated on multiple criteria.

NEST (NESA economics support tool). An instrument supporting the INPRO assessment in the area of economics. NEST comprises several models and options to calculate parameters necessary for the INPRO economic assessment. NEST converts basic technical and economic input parameters into standard functions used in economics (levelized unit energy cost, net present value, internal rate of return, etc.).

nuclear energy system (NES). A NES comprises the complete spectrum of nuclear facilities and associated institutional measures. Nuclear facilities include facilities for: mining and milling, processing and enrichment of uranium and/or thorium, manufacturing of nuclear fuel, production (of electricity or other energy- related products, e.g., steam, hydrogen), reprocessing of nuclear fuel (if a closed nuclear fuel cycle is used), and facilities for related materials management activities, including storage, transportation and waste management. Institutional measures consist of agreements, treaties, national and international legal frameworks, and conventions (such as the NPT, the International Nuclear Safety Convention, IAEA Safeguards Agreements) as part of the national and international infrastructure needed to deploy and operate a nuclear program. An example of a Nuclear Energy System could be a combination of thermal reactors and fast reactors, a closed fuel cycle based on plutonium/uranium, reprocessing facilities, centralized fuel production and waste management facilities.

nuclear fuel cycle. The series of steps in the front end, which are the preparation of the fuel, steps in the service period in which the fuel is used during reactor operation, and steps in the back end, which are necessary to safely manage, contain, and either reprocess or dispose of spent nuclear fuel.

roadmapping. A targets-oriented planning process to help identify, select, and develop alternatives to satisfy a set of certain requirements and provide information to make better decisions by identifying critical elements and gaps.

ROADMAP template. A flexible, multipurpose, and easy-to-use analytical tool providing specific guidance for developing national roadmaps and indicating weak points and gaps in a country's nuclear energy strategy. The tool allows to find out where, through collaboration with other countries, savings in time, efforts and resources needed for nuclear energy sustainability enhancement could be achieved.

ROADMAPS-ET (ROADMAPS Excel Tool). An analytical decision support tool for structuring and unifying data on issues related to enhancing sustainability of NES. The tool makes use of the Gantt charts, which are very popular in project management applications to illustrate project schedules and can also serve as one of the planning methods.

scenario. An image of a situation. a postulated or assumed set of conditions and/or events. A scenario describes a possible outcome of a sequence of events, based on assumptions about the events, their interplay and consequences. It commonly used in analysis or assessment to represent possible future conditions and/or events to be modelled.

sustainable development. The UN's general concept of sustainable development (*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*) and considerations specific to the concept of sustainable energy have been incorporated in the INPRO objectives and have been integrated into the INPRO methodology. The INPRO assessment methodology ensures that a given nuclear energy system takes into account the four dimensions of the UN's concept of sustainability: *social, environmental, economic and institutional infrastructure.* To address specific issues related to the development and deployment of nuclear energy systems (NES) for sustainable energy supply, INPRO has identified six topical areas of relevance to NES sustainability assessment, including *economics, environmental impact, safety, proliferation resistance, waste management and infrastructure, including physical protection*. While the INPRO subject areas are not aligned on a one-to-one basis with the four dimensions of sustainability set out in other UN initiatives, the structure chosen ensures that all relevant aspects of these dimensions are addressed.

sustainable nuclear energy system. A sustainable energy supply is an important requisite for a country to obtain sustainable development. Nuclear energy is one option for a sustainable energy supply system. In the INPRO methodology, a nuclear energy system is considered as sustainable if it contributes or at least can contribute to the sustainable development on the national, regional or global level. To check the sustainability of a nuclear energy system, the INPRO methodology was developed.
In the INPRO methodology, a nuclear energy system is sustainable if it complies with sustainability requirements that are elaborated in the INPRO methodology. A sustainable nuclear energy supply contributes to sustainable development. (HK)

user requirement (UR). A user requirement defines what should be done to meet the target/goal of an INPRO methodology basic principle. It is directed at specific institutions (users) involved in nuclear power development, deployment, and operation, i.e., the developers/designers, government agencies, facility operators, and support industries.

ABBREVIATIONS

AGR	advanced gas cooled reactor
AL	acceptance limit
ASENES	Analysis Support for Enhanced Nuclear Energy Sustainability
BP	basic principle
BWR	boiling water reactor
CAIN	calculation of actinide inventory
CLP4NET	Cyber Learning Platform for Network Education and Training
CR	criterion or criteria
EC	European Commission
EU	European Union
FINPLAN	Model for Financial Analysis of Electric Sector Expansion Plans
FR	fast reactor
GAINS	Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle
GCR	gas cooled reactor
GHG	greenhouse gas
HWR	Heavy water reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IEA/OECD	International Energy Agency / Organisation for Economic Cooperation and Development
IIASA	International Institute for Applied Systems Analysis
IN	indicator
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
INS	innovative nuclear energy system
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	internal rate of return

ISED	Indicators for Sustainable Energy Development
KI	key indicator
KIND	Key Indicators for Innovative Nuclear Energy Systems
KIND-ET	KIND Evaluation Tool
LWR	light water reactor
LUEC	levelized unit energy cost
MA	minor actinide
MAED	Model for Analysis of Energy Demand
MAVT	multi-attribute value theory
MCDA	multi-criteria decision analysis
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts
MESSAGE-NES	a tool for modelling nuclear energy systems with MESSAGE
MOX	mixed oxide
NES	nuclear energy system
NESA	nuclear energy system assessment
NEST	Nuclear Economics Support Tool
NFC	nuclear fuel cycle
NFCF	nuclear fuel cycle facility
NFCSS	Nuclear Fuel Cycle Simulation System
NPP	nuclear power plant
NPV	net present value
OECD	Organisation for Economic Cooperation and Development
O&M	operation and maintenance
PhD	Doctor of Philosophy
PHWR	pressurized heavy water reactor
PWR	pressurized water reactor
RBMK	high-power channel-type reactor
ROADMAPS	Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems

ROADMAPS-ET	ROADMAPS Excel Tool
R&D	research and development
RD&D	research, development, and demonstration
ROI	return on investment
SDG	Sustainable Development Goal
SIMPACTS	Simplified Approach for Estimating Impacts of Electricity Generation
SMR	small modular reactor
SYNERGIES	Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability
SWU	separative work unit
UN	United Nations
UR	user requirement
UO2	uranium dioxide
VVER	water cooled water moderated power reactor
WASP	Wien Automatic System Planning Package

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