Sustainability of Innovative Nuclear Energy Systems Using INPRO Methodology

Carolynn Scherer, Nilormi Das, Sera Jeon, Gaye Sayin

International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) Section, International Atomic Energy Agency (IAEA), Vienna International Centre, Wagramer Strasse 5, PO Box 100, 1400 Vienna, Austria, c.scherer@iaea.org

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INTRODUCTION

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) has worked towards sustainable usage of nuclear energy of innovative nuclear energy systems for almost 25 years. INPRO was established in the year 2000 by a General Conference Resolution of the International Atomic Energy Agency (IAEA) to examine innovative and proliferation resistant aspects of nuclear technologies.[1] The project, considered a Key Programme of the IAEA, is membership-based. Representatives of INPRO members form the INPRO Steering Committee that directly guides the project's activities.

One of the main objectives of INPRO is to ensure that sustainable nuclear energy is available to meet the significantly increasing energy demands of the 21st century. Secondly, INPRO brings together relevant stakeholders, both technology holders and technology users under a single roof to consider jointly the international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles which are economically competitive, possesses inherent safety features, minimizes proliferation concerns and environmental impacts.[2] The programme is forward-looking and holistic.

The vision of INPRO is to ensure that nuclear energy can contribute in a sustainable manner to the global energy needs of the 21st century and beyond. See Fig. 1.

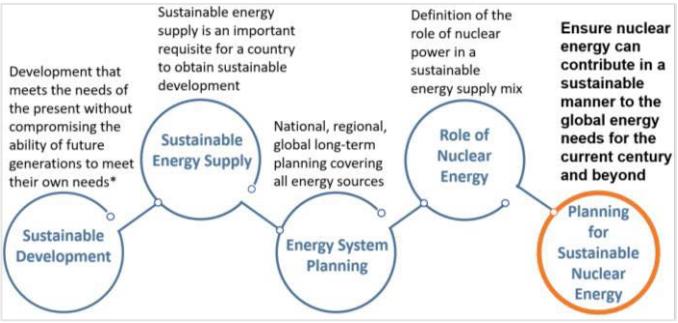

Fig. 1. A visual representation of the INPRO vision and mission.

The long-term mission of INPRO is to support Member State (MSs) in their long-term strategic planning for sustainable nuclear energy through utilization of the INPRO methodology, approaches, and tools. The objectives of INPRO are distributed amongst the following fours tasks.

Task 1 - Global Scenarios: is dedicated to modelling of scenarios, economic analysis, comparative evaluation, and analysis of nuclear energy systems (NESs), for developing a global vision of sustainable nuclear energy.

Task 2 - Innovations: investigates innovative nuclear energy technologies and institutional arrangements that support sustainable development of nuclear energy.

Task 3 - Sustainability Assessments and Strategies: helps MSs in developing sustainable, long-term nuclear energy strategies and supports deployment related decisions through use of the INPRO methodology.

Task4: Dialogue and Outreach: This task provides international platforms via dialogue forums and trainings to exchange ideas and information on long-term NES strategies, bringing together both technology holders and users.

BACKGROUND

The INPRO project developed a methodology for assessing sustainability of NESs based on the United Nations (U.N.) concept of sustainable development. According to the 1987 U.N. publication: Report of the World Commission on Environment and Development: Our Common Future, sustainable development was defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*"[3]. See Fig. 2.

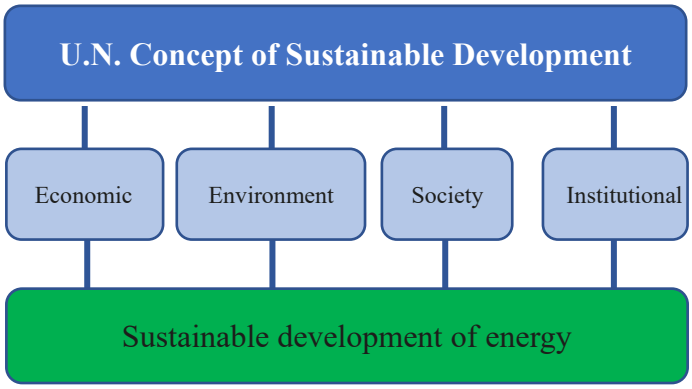

Fig. 2. United Nations concept of sustainable development from Brundtland commission report.

According to the report both developing and developed countries must commit to sustainable development, which has four key dimensions: economic, environmental, social, and institutional.

INPRO METHODOLOGY

Based on the UN dimensions for sustainable development of energy, INPRO developed a methodology to assess the sustainability of nuclear energy systems (NES). The INPRO methodology aligns with the UN dimensions using six key areas: (1) affordable economics, (2) minimal environmental impacts (including stressors and depletion of resources,) for societal concerning (3) safety, and (4) waste management, and for institutional (5) infrastructure, which requires that States can have an NES without an excessive investment in national infrastructure, and (6) proliferation resistance (which is part societal and institutional). The methodology is holistic, includes the entire lifecycle of the NES and covers a century of time. The development of the methodology was with the help of technical experts from across the globe. Additionally, the methodology undergoes regular updates.

The INPRO methodology also includes modelling and analysis of NES which supports strategic planning for nuclear energy development.

INPRO Methodology and Assessing for Sustainability

The INPRO methodology is in six key areas. Each area has its own basic principle. The basic principle is supported by user requirements (UR), with 2-7 URs per basic principle. The URs have criteria (CR), [1-7 CR per UR] that assessors use to determine if URs are met. If CR are met, than the UR is met and the NES is considered sustainable. Fig. 3 shows the hierarchy of the INPRO methodology for making a sustainability assessment of an NES or nuclear fuel cycle facility. When CRs are not fulfilled the NES is not sustainable and can be redesigned and reevaluated. For innovative systems, the assessment may find that research and development are needed to address the sustainability gaps.

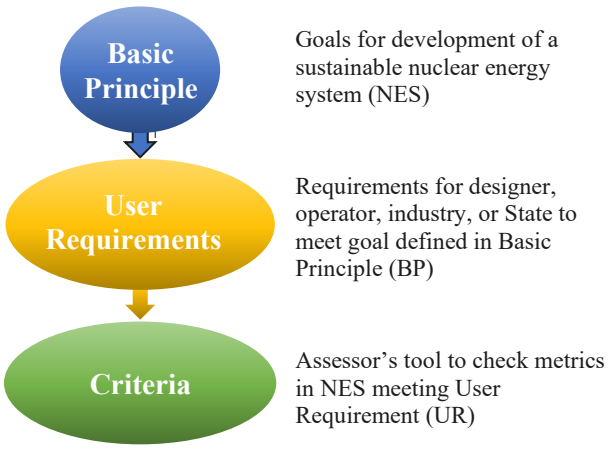

Fig. 3. Sustainability methodology showing basic principle, user requirement, and criteria.

Updated INPRO Methodology: Proliferation Resistance

In the last three years INPRO worked on updating the methodology in proliferation resistance. This recent update addressed a systematic review of the foundational framework. The basic principle was slightly updated to cover proliferation of nuclear weapons and nuclear explosive devices. The URs were kept at 5, however, they are more refined, and have fewer and better-defined CR. Additionally, the evaluation parameters, which typically have yes or no answers, make it easier for assessors to make the assessment. The Proliferation Resistance (PR) manual specifically addresses the state as the proliferator, assessing specifically the new nuclear materials, capabilities, and technologies which new facilities and processes are available to the State.[4]

The PR basic principle is *Proliferation resistance intrinsic features and extrinsic measures should be implemented throughout the life cycle of a nuclear energy system (NES) to help ensure that the NES will continue to be an unattractive means to acquire nuclear material for a nuclear weapon or other nuclear explosive device; both intrinsic features and extrinsic measures are essential, and neither can be considered sufficient by itself.* See Fig 5 for the PR hierarchy for BP, URs, and CRs.

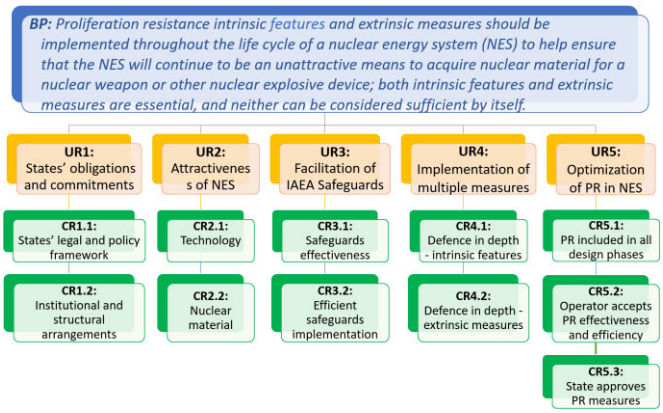

Fig. 4. The updated framework for an INPRO assessment in proliferation resistance.

The first UR assesses the State's obligations and commitments. This UR has 2 CR. The first regarding the states' legal obligations and commitments for addressing nuclear nonproliferation. The second CR regards national institutional and structural arrangements, especially the nuclear regulatory authority and others.

The second UR examines the attractiveness of the NES to the State. The CR assess the isotopes and quantity of material useful for making a nuclear weapon or nuclear explosive device, so it goes beyond the isotopes in a safeguards agreement. This UR also examines the capabilities in the state, including reprocessing, fabricating nuclear fuels and others. This UR is different than others as the attractiveness for assessment is low, medium, high and very high for the attractiveness of nuclear material and

technologies for creating a nuclear weapon or explosive device.

The third UR is the facilitation of IAEA safeguards, that they are effective and can be implemented efficiently. If a State has had an IAEA State System of Accounting and Control Advisory Service (ISSAS), it makes it easier to answer this UR.

The fourth UR is the implementation of multiple intrinsic features and extrinsic measures and to cover diversion paths, which is a defense in depth concept. The more attractive the nuclear material and technologies in an NES, the more measures and features needed to cover these proliferation concerns.

The fifth UR is for the operator, that the PR implemented is acceptable to the operator and the State. The PR measures are efficient and acceptable to the operator, so the NES can meet PR concerns while still being profitable.

Sustainability of Innovations

Amongst various collaborative projects of INPRO, one of which is FRAMES, the Framework for modelling energy systems; this model involves developing a tool to support Member States (MSs) in analyzing and optimizing energy systems that combine renewable energy sources with nuclear energy.

The INPRO program has a lot of involvement in innovative areas. Two of the most recent collaborative projects are in legal and institutional issues of prospective deployment of (1) fusion facilities and (2) nuclear hydrogen systems.

Other projects involve working with MSs in assessing the sustainability of nuclear energy systems with small modular reactors (SMRs). The first looks at global and regional scenario options for NES that use SMRs. Another uses the INPRO methodology to assess if there are gaps in sustainability.

The project supports and conducts training sessions in strategic planning for sustainable nuclear energy development. INPRO is partnering with MSs in preparing a curriculum and designing courses for master's program on strategic planning for sustainable nuclear energy. These efforts support MSs in future building capacity for nuclear programs nationally, thus supporting sustainability.

RESULTS

The INPRO program addresses MSs needs for assessing sustainable development and deployment of nuclear energy, and in bringing MSs together to develop global and regional scenarios involving NES for their long-term deployment.

The fusion collaborative project is working to identify some of the legal and institutional impediments in deploying innovative fusion facilities. One needs to consider the proliferation resistance and the application of IAEA safeguards. The project team noted that the INPRO methodology was adequate to address gaps in sustainability and impediments to deployment of fusion facilities.

The INPRO methodology and tools continue to support member states in meeting U.N. sustainable development goals. There are currently 17 sustainable development goals,[5] see Fig. 5. INPRO activities addresses these U.N. sustainability goals, either directly or indirectly. The INPRO program supports MSs in developing sustainable strategies for energy security.

Fig. 5. The U.N. now has 17 sustainability development goals, as shown in the figure.[5]

CONCLUSION

The INPRO program continues to support MS in innovative energy planning, such as in nuclear hydrogen production and fusion energy. These two areas are on the brink of innovations. The INPRO methodology for addressing sustainability is helping MSs to meet net zero goals. In 2023 the INPRO Steering Committee recommended a new collaborative project, which INPRO is initiating in 2024, to transition fossil-fueled power plants to nuclear energy. This project should help members meet their climate and net zero CO_2 emissions goals. INPRO has a project dealing with recycling of fuel and evaluating the back end of the fuel cycle; this is an important study for addressing the long-term sustainability of NES. Another INPRO project is the deployment of transportable nuclear power plants (TNPPs). The INPRO methodology, approaches, and tools, are suitable for supporting MSs in meeting the challenges of deploying sustainable nuclear and other innovative energy sources.

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