Recent Applications of the INPRO Methodology for Innovative and Advanced Nuclear Energy Systems

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ABSTRACT

Sustainable development is the notion that human societies must exist and fulfil their needs without compromising the ability of subsequent generations to meet their own needs, as defined by the 1987 Brundtland Report. The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) implemented the United Nations' concept of sustainable development of energy to assess the sustainability of nuclear energy systems and developed a methodology in this context. Member States can use the INPRO methodology for their long term-planning for the deployment of sustainable nuclear energy. The INPRO methodology encompasses the following six subject areas: economics, environmental impacts, infrastructure, proliferation resistance, safety, and waste management. Member States can use the INPRO methodology to do a Nuclear Energy Systems Assessment (NESA), which is a sustainability assessment of a State's nuclear energy system, or a part of the system, such as a reactor. These assessments identify gaps in sustainability, which designers can address during design phases or State should address to close the gaps. There are many recent NESA publications covering a variety of innovative nuclear energy systems. Many countries, including newcomer countries, used NESA process to evaluate sustainability of a variety of nuclear energy systems, including nuclear power plants, fuel fabrication facilities, and experimental reactor facilities. Some assessments covered all six areas, while other assessments were limited, covering only one or a few areas. These self-assessments on sustainability support Member States in decision making for the implementation of these innovative nuclear energy systems, showing that the NESA process is applicable to innovative and advanced nuclear energy systems.

INTRODUCTION

The definition of sustainable development, according to the Brundtland Report in 1987, is "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." [1] The concept of sustainable development has become more prominent through different United Nations (UN) led efforts, such as Agenda 21, the Commission on Sustainable Development, and the World Energy Assessment [2]. The basis for the UN concept of sustainable development is economics, environment, society, and political [1]. The establishment of a future that is inclusive, sustainable, and able to withstand challenges requires collaborative endeavours.

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), launched by the International Atomic Energy Agency (IAEA) in 2000, applied the United Nations' sustainable development concept to evaluate the sustainability of nuclear energy systems and to develop a methodology for this purpose. The INPRO methodology is a comprehensive framework that aligns with the UN concept of sustainable energy development and provides guidance for the development and deployment of innovative nuclear energy systems based on six areas: infrastructure, economics, safety, environmental impacts, waste management and proliferation resistance. The objectives of INPRO are to ensure the availability of nuclear energy as a sustainable solution to meet the world's energy demands in the current century and beyond; and to bring together all interested Member States in joint international and national tasks on innovative nuclear reactors and fuel cycles [3].

The INPRO methodology and services help Member States achieve sustainable nuclear energy systems that meet their national energy needs while addressing global energy and environmental concerns. As of April 2023, INPRO has the support of 43 Member States and the European Commission.

Nuclear Energy System Assessment (NESA) is a sustainability tool that focuses on the assessment of a nuclear energy system in the six key areas to identify gaps in sustainability. The aim of a NESA is to provide a comprehensive framework for evaluating and improving the sustainability performance of nuclear energy systems and to help countries achieve their sustainable nuclear energy development goals. Designers and other users have the opportunity to evolve the design to address the gaps found in a NESA, making the NES sustainable over its lifetime.

INPRO Methodology for Sustainable Development

The INPRO NESA is a holistic assessment of given nuclear energy system (NES) with the goal of determining its long-term sustainability. The NESA is a valuable tool that assists decision-makers regarding the sustainable implementation, maintenance, or enlargement of nuclear power programmes [2]. Member States can use the INPRO methodology for their long term-planning for the deployment of sustainable nuclear energy. The ultimate goal of the application of the INPRO methodology is to check whether the nuclear energy system assessed fulfils all the criteria and hence the user requirements and basic principles, and therefore represents a long-term sustainable system for Member States.

The INPRO methodology encompasses the following six subject areas: economics, environmental impacts, infrastructure, proliferation resistance, safety, and waste management. Member States can use the INPRO methodology to do a NESA, which is a sustainability assessment of a State’s nuclear energy system, or a part of the system, such as a nuclear reactor. Additionally, assessments may occur only in targeted area(s), and these are known as limited scope assessments. See Figure 1. The INPRO assessments identify gaps in sustainability, which designers can address during design phases or State should address to close the gaps. For innovative systems the NESA can identify gaps in sustainability that need research and development (R&D) to close.

Figure 1. Diagram showing the INPRO sustainability assessment areas.

Application of INPRO Methodology

There are numerous recent publications covering the use of the NESA to assess the sustainability of various innovative nuclear energy systems. Member States performed these assessments, including those new to nuclear energy, and have covered a range of facilities such as nuclear power plants, fuel fabrication plants, and experimental reactors. Indonesia, Saudi Arabia, Chile, Russian Federation, and Pakistan applied the INPRO methodology to assess various aspects of their nuclear energy programs. While some of these assessments evaluated all six areas, others focused on specific areas. These self-assessments can help Member States in informing policy and decision makers regarding the implementation of sustainable advanced nuclear energy systems.

Saudi Arabia

In 2019, Saudi Arabia conducted an economic analysis to evaluate the deployment of the VVER-1000 reactor, using the INPRO methodology for economics [4]. The study was conducted to support developing countries in the deployment of nuclear energy in a sustainable manner. The assessor used Jordan as an example of a newcomer country for introducing nuclear power into the energy mix through the deployment of a VVER-1000 reactors. The basis for the assessment was the INPRO Manual: Economics from 2014 [5].

The study did a sensitivity analysis of the cost input data. The discount rate and the capacity factor had the highest sensitivity on the levelized cost of electricity (LCOE), see Figure 2. The NESA study in economics concluded that “the levelized cost of nuclear electricity presented in this study could assist governments interested in introducing nuclear power into their energy mix, to develop an energy policy that is country and technology specific [4].”

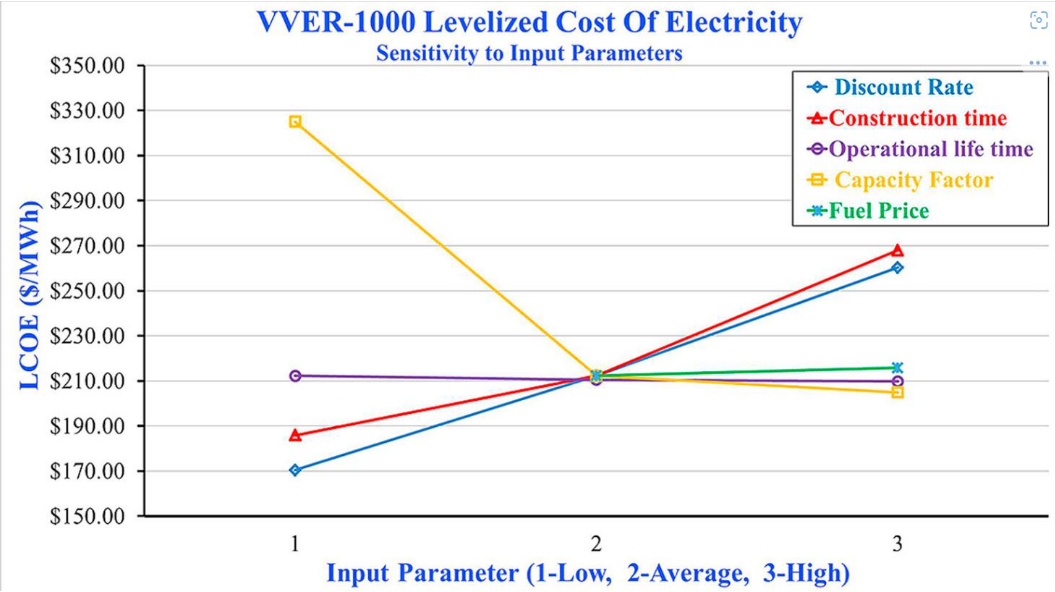

Figure 2. Sensitivity analysis on the levelized cost of electricity (LCOE) for the VVER-1000 nuclear reactor economics study [6].

In February 2022 Saudi Arabia "confirmed the establishment of the Saudi Nuclear Energy Holding Company (SNEHC), which will act as the country's nuclear developer [7]." Although Saudi Arabia currently does not possess any commercial nuclear power plants, it has demonstrated aspirations to implement roughly 17 GW of nuclear energy by 2040 [8].

Chile

In 2021, Chile, conducted an assessment to support the Energy Policy 2050, specifically to address incorporating nuclear energy into the electricity generation mix [9]. The objective was to compare nuclear reactor alternatives based on technical and economic aspects using the INPRO methodology in economics [5]. The objective was to support decision-making by evaluating and prioritizing advanced nuclear reactor designs on a technical basis. The study covered mostly small modular reactor designs as shown in Table 1. The study focused on five areas, economics [5], environmental stressors [10, 11], waste management [12], safety [13, 14], and proliferation resistance [15]. Chile did not assess infrastructure because within the social, political, and institutional context, the assessment results would be the same regardless of the nuclear reactor. Additionally, since most of the criteria from the other INPRO assessment areas would be independent of the nuclear reactor the study mostly focused on economics [9]. The study combined the INPRO Methodology with a multi-criteria analysis (MCA) technique and application of the multi-criteria decision analysis methods to comparative evaluation (INPRO KIND) [16] for prioritizing the nuclear reactors.

Table 1. Characteristics of nuclear power plants for Chilean INPRO NESA

Model (year data)	Type	# units/plant	Unit/Total Electrical Power (MW)
ACP100 (2018)	iPWr	5	125/625
EC-6 (2011)	HWR	1	740/740
NuScale (2020)	iPWR	12	60/720
SMART (2011)	iPWR	6	100/600
SVBR-100 (2010)	LFR	6	100/600

VVER-600 (2011)	PWR	1	600/600

The study ranked the reactors based on three scenarios, with varied weighting factors, as listed below.

- Scenario 1: Each criteria weighs the same, however categories with more criteria have higher priority
- Scenario 2: Priority for criteria based on Chile Energy Policy 2050; more importance given to criteria in governmental reports and policy
- Scenario 3: Same priority given to each category of criteria; the unbiased case [9]

The comparative rankings for the reactors based on the study are in Table 2. The study showed a comprehensive and quantitative approach to evaluating nuclear reactors for energy production, which took into account multiple sustainability criteria and prioritized advanced reactor designs for meeting the energy needs of the future while minimizing negative impacts on the environment and society [9].

Table 2. Comparative rankings for SMR in Chilean INPRO NESA

Ranking	Scenario 1	Scenario 2	Scenario 3
1	NuScale	SVBR-100	EC-6
2	EC-6	NuScale	NuScale
3	SMART / SVBR-100	EC-6	SMART
4	-	VVER-600	SVBR-100
5	VVER-600	ACP100	ACP100
6	ACP100	SMART	VVER-600

Chile has no nuclear power plants and has not taken any decision regarding the development of a nuclear power program. However, Chile has a strong background on other nuclear applications such as nuclear medicine, radiopharmaceuticals, and radiation therapy. Also, Chile has a history in using nuclear techniques in agriculture, food safety, and environmental monitoring [17].

Pakistan

In 2019, Pakistan conducted an assessment on molten salt reactors (MSRs) using the INPRO Methodology [18] in safety [19]. Table 3 lists the MSR concepts covered in the assessment.

Table 3. Overview of some MSR concepts [18]

Reactor	IMSR-400	LFTR	SmAHTR	MSFR	MSFR-FUJI
Designer country	Canada	USA	USA	France	Japan
Fuel type	UF4 in diluent fluorides	Th-U cycle	TRISO	Actinide fluorides of Th & U-233	Th-U molten Salt
Neutron spectrum	Thermal	Thermal	Thermal	Fast	Thermal
Moderator	Graphite	Graphite	Carbon	No solid moderator	Graphite

Based on the available data, the assessment concluded that the molten salt technology satisfies many of the safety requirements specified by the INPRO methodology. However, certain criteria pertaining to occupational and public doses were not met due to lack of data provided by designers. The study mentioned that “INPRO methodology is a very powerful tool as it applies to both operational reactors and reactors in the design phase [18]”. The INPRO methodology proved helpful in identifying areas that require further research and improvement, and provided a framework for the evaluation of nuclear energy systems that are compatible with global sustainability objectives [18]. Pakistan currently has six operational reactors, provided by China [20].

Russian Federation

The Russian Federation has a lot of experience in applying the INPRO methodology. In 2021, study was for a multi-criteria comparative evaluation of Russian's nuclear energy plan based on different shares of thermal and sodium-cooled fast reactors. Options involved the use of MOX fuel in VVER reactors, and the analysis used the INPRO MESSAGE-NES tool. The findings demonstrated that, when considering multiple performance indicators, deployment of sodium-cooled fast reactors and the transition to a closed nuclear fuel cycle can enhance the sustainability of the Russian nuclear energy system [21].

In 2021, the Russian Federation with the IAEA conducted an INPRO sustainability assessment for an innovative nuclear energy system based on the BN-1200 fast reactor [22] in the areas of economics [5] and the updated manual for safety of nuclear reactors (2020) [13]. The reference reactor for the safety analysis was the BN-800. The INPRO assessment in the safety area showed significant promise in contributing to the development of INPRO safety assessment approaches for sodium cooled fast reactors. The sustainability assessment helped in understanding the differences between defense in depth implementation in fast reactors and that in water-cooled reactors in the INPRO area of nuclear safety [22]. Some areas could not be assessed due to lack of design information. An updated full assessment, based on a more complete set of data, should be done in the future to make a judgement on the sustainability of the BN-1200.

Indonesia

Indonesia has some of the most extensive experience in application of the INPRO methodology for NESAs. See Table 1 for a detailed list of Indonesia's NESAs.

Table 4. Indonesia's NESA Activities

Year, Facility [Ref]	NESA Areas	Assessment Outcomes
2022 **High Temperature Reactor (HTR) fuel programme** [23].	Economics [5]	Small deployment not economically feasible Redo for a larger deployment (consider exporting fuel)
	Infrastructure [24]	National strategy needs long-term commitment to funding availability, and international cooperation
	Waste Management [12]	Long-term planning for waste management
	Environmental Impacts – from Stressors [10] and Depletion of Resources [11]	Stressor assessment postponed to next phase
	Proliferation Resistance [25]	Newcomer countries collaborate with international partners and involve the IAEA
	Safety [13, 14]	Needs in depth assessment when more date is available
2019 **10 MWt experimental power reactor (RDE)** [26]	Proliferation Resistance [25]	Strong proliferation resistance, particularly in terms of the diversion and detectability of nuclear material Requires further assessment for the safeguards system
2023 **SMR and**	Economics [5]	Compared to coal plants Both NPP and SMR are comparable to fossil fuel energy SMR competitiveness may improve with carbon charge

Year, Facility [Ref]	NESA Areas	Assessment Outcomes
GEN III+ NPP [27]		on fossil fuel
	Infrastructure [28]	In place and can make available necessary infrastructure Should seek regional and international cooperation
	Waste Management [12]	Need to address management of radioactive waste and spent fuel Address final disposition of fuel
	Environmental Impacts – from Stressors [10] and Depletion of Resources [11]	Uranium availability is good Should address availability of some non-renewable resources
	Proliferation Resistance [29]	No specific issues, under IAEA safeguards
	Safety [13, 14]	Selected designs offer confidence to sustain safe operation through lifetime Need to convey message to stakeholders and public
	Physical Protection [1575 Vol. 6]	May need to address contingency plans, radiological consequences of sabotage, and recovery of nuclear material

Some outcomes from Indonesia's NESAs are that the INPRO Methodology supports sustainability and is important for the "long-term strategy and national commitment when establishing a HTR fuel program [23]." Application of all INPRO assessment areas is needed to acquire a holistic understanding of sustainability and design improvements [26].

In December 2022 the government announced a goal for a nuclear power plant by 2039 [30]. In March 2023, the United States and Indonesia declared a strategic alliance aimed at assisting the advancement of nuclear energy that emphasizes clean energy. This partnership aims to use small modular reactor (SMR) technology to achieve its energy security and environmental objectives [31]. Indonesia has some experience and infrastructure in the field of nuclear technology and plans to construct an experimental nuclear power reactor with a capacity of 10 MWe in Jakarta [30].

Resources for Performing a NESA

There are many resources to help in performing a NESA. To assist assessors there are INPRO manuals for each assessment area. See Figure 3. The IAEA INPRO section is working on the publication of two new resources, the INPRO Manual in Proliferation Resistance and an Introduction to the INPRO methodology as shown in Figure 4. Additionally, INPRO has a Wiki page with the INPRO manual in digital format and checklists that cover each assessment area available to help with the NESA [32]. See Figure 5. Additionally, INPRO is available to assist with training, and missions to support NESA for Member States NES assessments for sustainability.

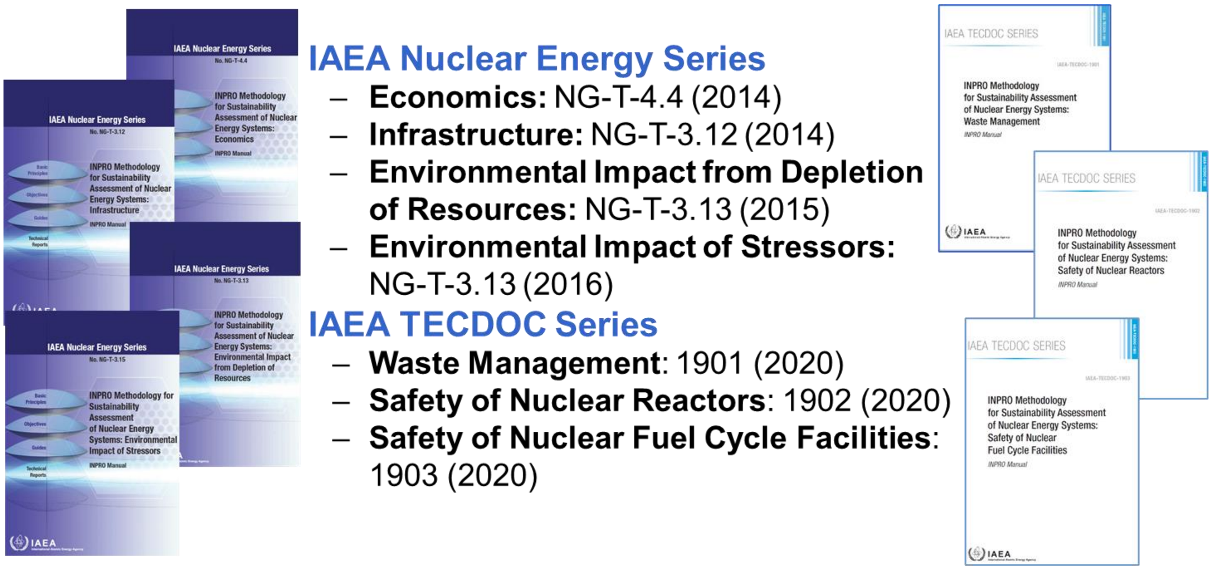

Figure 3. The assortment of the INPRO manuals for performing a NESA.

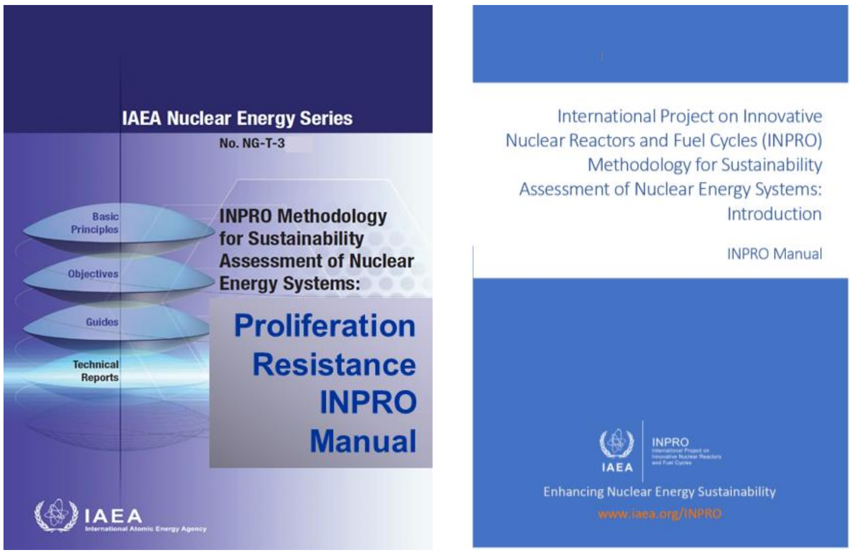

Figure 4. The new INPRO manuals, one for Proliferation Resistance and the other covering an Introduction to the INPRO Methodology.

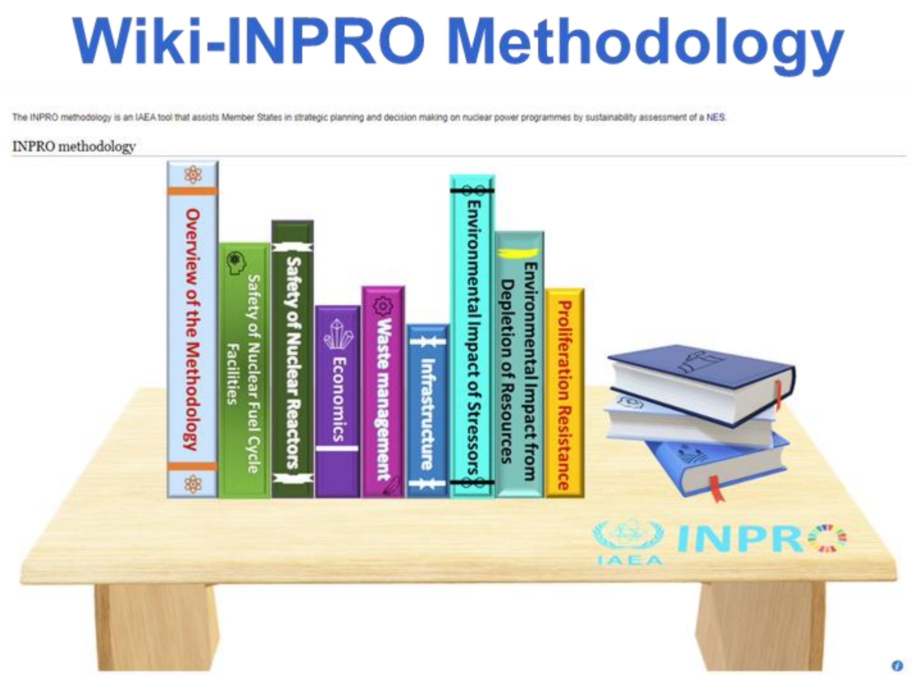

Figure 5. Screenshot of INPRO Wiki page.

CONCLUSIONS

The INPRO methodology is a valuable tool for promoting the sustainable development of NES. Several countries, including Indonesia, Saudi Arabia, Chile, Russian Federation and Pakistan, used the NESA process to evaluate the sustainability of a variety of NES, which covered nuclear power plants, small modular reactors, fuel fabrication facilities, and experimental reactors. The INPRO methodology provides a comprehensive framework for evaluating sustainability of NES and identifying gaps, which can be addressed during design phase and prior to construction. The application of the INPRO methodology addresses six key areas of sustainability: economics, infrastructure, environmental impacts, safety, waste management, and proliferation resistance. The methodology provides a structured and holistic approach to evaluating NES that takes into account a range of technical, economic, and social factors which cover UN sustainable development goals. These INPRO sustainability assessments represents a valuable contribution to the ongoing discussion surrounding the future of nuclear energy and its role in meeting global energy needs while addressing concerns about climate change and attaining net zero target goals.

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