Using INPRO Methodology for a Sustainability Assessment of Advanced and Innovative Small Modular Reactors

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ABSTRACT

Deploying small modular reactors (SMRs) is a highly promising concept with the possibility of reducing greenhouse gas emissions as well as meeting world electricity requirements competitively, efficiently, and reliably. Many SMR designs have a power capacity around 300 megawatts electric. These SMRs are essential for matching increasing energy demands in developing countries due to significant reduction in construction and operation costs, and fast deployment. However, an essential requirement for SMR deployment is their sustainability, especially for advanced or innovative designs. The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), launched in 2000 at the IAEA, focuses on ensuring nuclear energy is available in the 21st century and beyond in a sustainable manner. The project developed a Nuclear Energy System Assessment (NESA) which is a criteria-based sustainability assessment covering 6 key areas, such as safety, economics, waste management, environmental impact, infrastructure, and proliferation resistance. Additionally, a key part of the INPRO methodology is to cover the life cycle of the nuclear energy system. Using the INPRO methodology and NESA is a key factor for technology holders, designers, and States to identify gaps and weaknesses in innovative nuclear reactors and fuel cycles. Recent work shows that the INPRO methodology and NESA process are applicable in assessing advanced and innovative SMRs to identify gaps and weaknesses in sustainability prior to State's deploying SMRs.

1. Overview of Nuclear Energy System Assessment (NESA) Process

The INPRO methodology is useful in performing a nuclear energy system assessment for a holistic assessment of sustainability of a particular nuclear energy system (NES). This assessment aims to either validate the NES's long-term sustainability or identify shortcomings or gaps that require attention. Consequently, the nuclear energy system assessment (NESA) serves as a valuable tool for guiding decision-making related to the sustainable implementation or expansion of nuclear energy programs.

The INPRO methodology, first presented in 2003 [1], helped address public apprehensions of nuclear energy. The concerns covered safety, economics (high cost of nuclear power), institutional structures (including proliferation), and the environment (waste management) [2]. The INPRO sustainability assessment covers NES and facilities from design, through construction, operation, and decommissioning, over approximately a century of time, and longer for waste management. There are six assessment areas: (1) environment, (2) safety, (3) proliferation resistance, (4) waste management, (5) infrastructure, and (6) economics. In 2008 there was publication of an updated INPRO methodology presented in nine manuals [3]. More recent updates to the INPRO methodology began in 2014, based on recommendations from sustainability assessments and input from international experts and Member State experience with the INPRO methodology. As a result, the INPRO methodology for a sustainability assessment consists of the following nine manuals.

1. Overview – IAEA TECDOC-1575, Volume 1 (2008) – slated for update [3]
2. Economics – IAEA Nuclear Energy Series, No. NG-T-4.4, August 2014 [4]
3. Infrastructure – IAEA Nuclear Energy Series, No. NG-T-3.12, August 2014 [5]
4. Waste Management – IAEA-TECDOC-1091, March 2020 [6]
5. Proliferation Resistance - IAEA Nuclear Energy Series –in publication review
6. Environmental Impact from Depletion of Resources – IAEA Nuclear Energy Series, No. NG-T-3.13, December 2015 [7]
7. Environmental Impact of Stressors - IAEA Nuclear Energy Series, No. NG-T-3.15, July 2016 [8]
8. Safety of Nuclear Reactors – IAEA-TECDOC-1902, March 2020 [9]
9. Safety of Nuclear Fuel Cycle Facilities - IAEA-TECDOC-1903, March 2020 [10]

According to the INPRO methodology, a NES encompasses all components in the fuel cycle - from the front end: mining and milling to conversion, enrichment, and fuel fabrication - as well as the reactor and the back end: reprocessing (if applicable), and waste management. INPRO methodology assesses both innovative and evolutionary nuclear facility designs for short-term and long-term deployment [3].

The INPRO methodology is hierarchical, beginning with a basic principle (BP) for each assessment area. The BP is a target that the NES should achieve to be sustainable in the long term. Subsequently, each BP has user requirements (URs), which define how to meet this 'basic principle' target. The URs are supported by criteria (CR). To aid in the assessment CR have evaluation parameters (EPs), which help standardize the assessments. An assessor uses the EP to determine whether the CR is met. When the CR is met then the UR is met. When URs are met, then the BP is met and the NES has sustainability [4, 11]. The INPRO methodology has usefulness a diverse group of users, including nuclear technology developers, experienced technology users, and countries embarking on or expanding their nuclear energy programme. The INPRO methodology can be applied at different levels of depth and scope.

Limited Scope Assessment: to assess a NES or a single component in one or more selected areas.
Full Scope Assessment: covers all components in NES and all assessment areas.

In countries new to nuclear power, embarking countries, the INPRO methodology can be utilized at various stages of development within a new nuclear power programme to support sustainable development and deployment of energy sources [11].

The NESA begins with an energy system planning study that outlines the projected energy requirements of a country (or a region, or the world) and the role or contribution of nuclear power in meeting those needs. Next, the assessors should identify the scope and objectives of the NESA. Based on the areas of the assessment, an assessment team should be formed. Figure 1 is a graphical representation of the steps in performing a NESA to develop a sustainable NES. These NESA activities have recently been done on small modular reactors (SMRs).

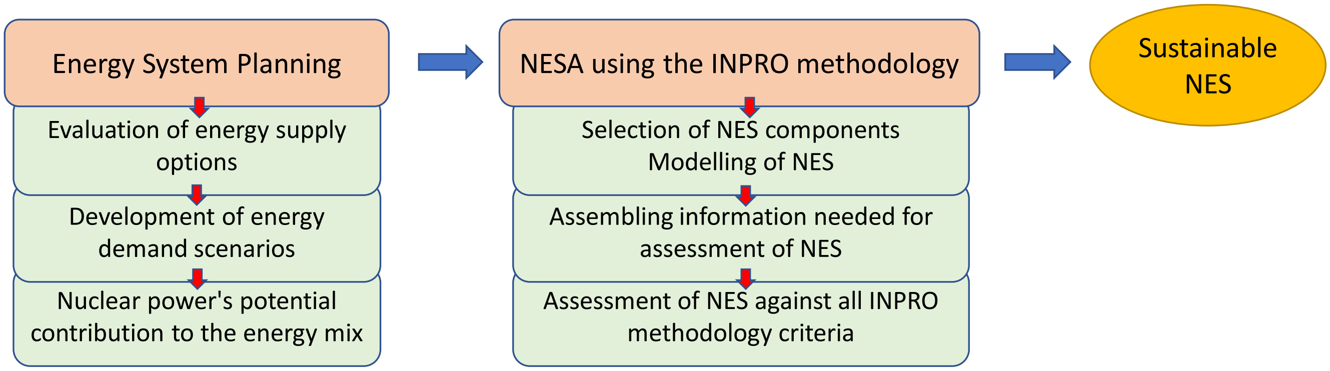

FIG. 1. Energy system planning steps and INPRO methodology for NESA [3]

2. NESA SMR Performed by Member States (Indonesia Case Study)

To reach and sustain Net Zero goals Indonesia is planning to introduce nuclear power including deployment of small modular reactors. Indonesia performed a NESA to identify gaps and weaknesses in sustainability prior to deploying SMRs over the entire INPRO methodology. The NESA for the SMR (currently on-going) [12] and a large scale NPP [13] (was published in 2015). This paper examined the Indonesia NESAs in two areas, economics and infrastructure.

2.1 Limited scope NESA in the area of economics

The goal of an INPRO sustainability assessment in the area of economics is to evaluate the competitiveness of nuclear power in comparison to other available alternatives. This assessment is independent and focuses on ensuring that energy and related products and services provided by a nuclear energy system (NES) are accessible and affordable. To achieve this goal, the assessment is guided by one fundamental principle, four user requirements, and eight criteria. In table 1 an overview of the INPRO economic assessment is presented.

Table 1. Overview of the INPRO Methodology for Sustainability Assessment in Economics [4]

User Requirement (UR)	Criteria (CR)
Economics BP: *Energy and related products and services from nuclear energy systems shall be affordable and available.*	
UR1: Cost of energy The cost of energy supplied by NES, taking all relevant costs and credits into account, C_N, should be competitive with that ofalternative energy sources, $C_{A.}$ that are available for a given application in the same time frame and geographic region/jurisdiction.	**CR1.1: Cost competitiveness**
UR2: Ability to finance The total investment required to design, construct, and commission NES, including interest during construction, should be such that the necessary investment funds can be raised.	**CR2.1: Attractiveness of investment**
	CR2.2: Investment limit
UR3: Investment risk The risk of investment in NES should be acceptable to investors.	**CR3.1: Maturity of design**
	CR3.2: Construction schedule
	CR3.3: Uncertainty of economic input parameters
	CR3.4: Political environment

User Requirement (UR)	Criteria (CR)
UR4: Flexibility Innovative NES should be compatible with meeting the requirements of different markets.	**CR 4.1: Flexibility**

To help compare costs of nuclear energy with alternative energy sources, the IAEA developed the NESA Economic Support Tool (NEST). The Indonesian calculation team used this tool to carry out a NESA in the area of economics. It allows assessors using the INPRO methodology to easily determine numerical economic parameters such as levelized unit energy cost (LUEC), internal rate of return (IRR), return on investment (ROI), net present value (NPV), for nuclear power plants (NPPs) and alternative systems like fossil fuel plants. [4]

Description of the Power Plants that compete with SMR

To conduct the economic assessment for SMR deployment, the NESA compared nuclear energy facilities to coal power plants (CPPs) with a similar capacity [12]. Figure 2 shows the preliminary results for the NESA in economics for the SMR deployment. For the NESA only the first criterion was partially met, while all other criteria were not met. The figure shows criteria that need to be addressed to make SMRs sustainable in Indonesia.

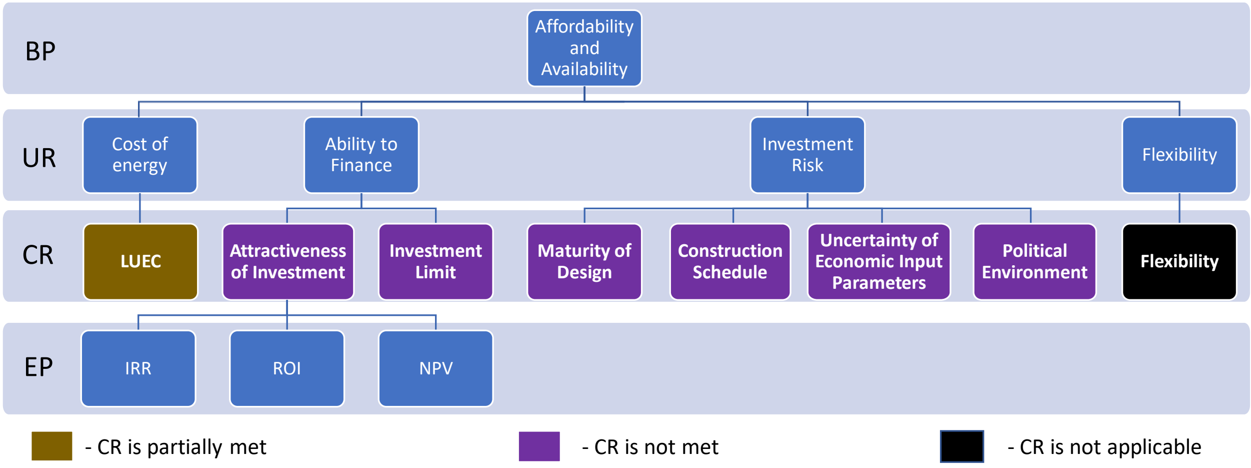

FIG. 2. NESA of SMR deployment in Indonesia in the area of economics [12]

The NESA report for a large nuclear power plant (PWR 1115 MWe) includes a comparison of nuclear energy with alternative power sources with several types of CPPs [13]. Preliminary Results for the NESA of the full-size NPP deployment in Indonesia in the area of economics appear in the Figure 3. The NPP met half of the criteria, while 2 CRs were not met, and 1 CR is only partially met. The following sections give a more detailed description for some of the CRs.

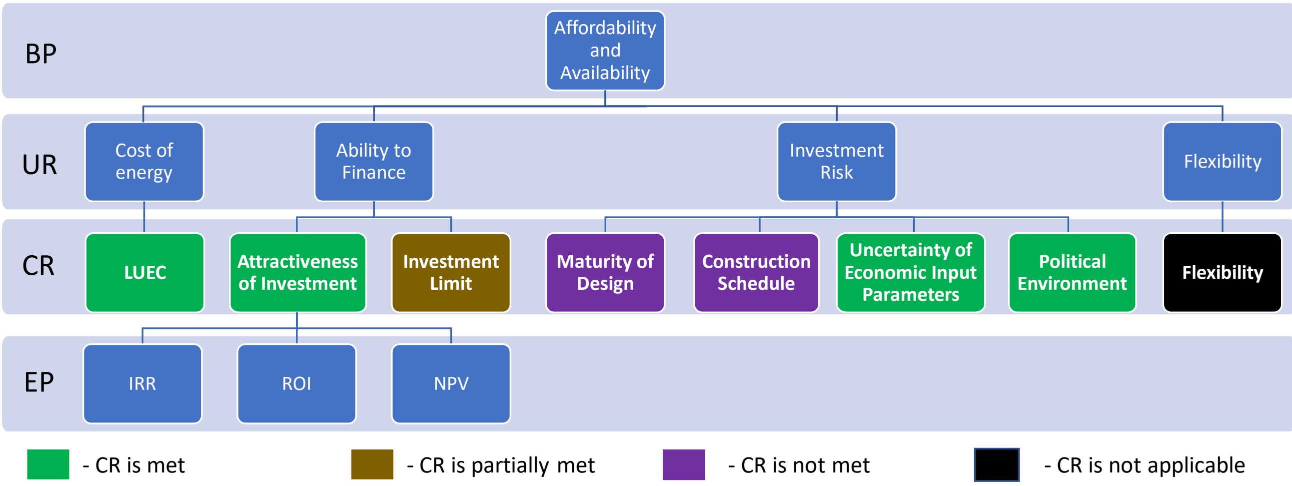

FIG. 3. Results from NESA of large-size NPP deployment in Indonesia [13]

Criterion CR2.1 – Attractiveness of Investment

The evaluation of CR2.1 in the NPP case uses the NPV, the IRR, and ROI. The NPV measures the absolute profitability and accounts for the time value of money by employing a discount factor to balance the present cost versus the future revenue (is typically based on the weighted average cost of capital (WACC). The IRR is a specific dimensionless indicator that denotes the WACC value that equates the NPV to zero. The higher the IRR, the more profitable is the investment [14]. The ROI is calculated from the average net annual income and expressed as a fraction of the capital invested in the NES.

SMR: The IRR and ROI were lower for most SMRs for the n^{th} of a kind (NOAK). Thus, CR2.1 is not met. Compared to other technologies, SMRs exhibit a lower financial feasibility and slower ROI, with only the SMR NOAK having the potential to compete with most CPPs.

Large NPP: The IRR for large NPP is higher than alternative sources of energy. Similarly, the ROI for nuclear is higher than those for gas and CPPs. Therefore, large NPPs are financially more feasible than both fossil technologies, with a faster ROI. Hence, CR2.1 is met.

Criterion CR2.2 – Investment Limit

The indicator for CR2.2 is the total investment required for the project. The CR is met when the financial resources invested could be raised during the life span of power plant.

SMR: According to the results, the investment cost of SMR FOAK (first of a kind) is the highest at 584 million US dollars, which is approximately 1.5-3.75 times higher than the costs associated with CPPs. [12] Thus, immaturity of SMR projects due to lack of existing commercial projects and connected with the costliness of the FOAK plant construction, makes it difficult to meet this CR.

Large NPP: Overnight construction cost (in US dollars per kWe) is competitive in comparison with modern gas and CPPs. Thus, in terms of total investment large NPPs can compete with gas and CPPs and the CR is partially met, taking into account the overnight construction cost of the conventional large NPP (1115 MWe) exceeds 4 billion US dollars and the net electric power is almost two times bigger than alternatives (600 MWe). [13]

Criterion CR3.3 – Uncertainty of Economic Input Parameters

The CR3.3 is based on a sensitivity analysis of important input parameters for calculating costs and related financial figures of merit [4]. These sensitivity analyses can be done using NEST.

SMR: Because of their smaller capacity and higher cost per generated unit of energy SMRs have a higher sensitivity when changing input parameters. This CR is not met as SMRs show less robustness against alternative sources of energy. To facilitate the deployment of SMR, the government should establish a policy, such as providing a special high price per unit of electricity sold (PUES), as it is already implemented for renewables and other energy sources used in remote locations. [12]

Large NPP: Compared to other alternatives, nuclear energy in the form of large NPPs exhibits excellent resilience when facing construction schedule delays, changes in discount rates and fuel costs, and plant lifetime perturbations. Thus, the criterion is met. [13]

Criterion CR3.4 – Political Environment

This CR specifically addresses the political support for nuclear power in a country [4].

SMR and Large NPP: According to Presidential Regulations from 2005-2006, the Indonesian government's energy policy has deemed nuclear power an essential part of the optimal energy mix. At the time of carrying out the NESA for large NPP in 2015, the commitment was considered sufficient as the criterion was met. [13] However, with the ongoing NESA for SMR, the team has recognized the need for the government to take tangible steps towards implementing these regulations. [12]

Criterion CR4.1 – Flexibility

This criterion seeks flexibility for selling the new design under different market conditions. While the ability to adapt specific components and the overall system for different energy applications and fuel types is desirable, it is not considered essential. The UR/CR on flexibility was added in later INPRO manuals on economics [4], so not many published assessments addressed this CR. Indonesia chose not to evaluate this UR due to a lack of information from the SMR vendor. Another NESA [15] attempted to cover the UR by assessing the flexibility of the nuclear fuel cycle, but the lack of information on reactor operation prevented a comprehensive evaluation.

2.2 Limited scope NESA in the area of infrastructure

The Infrastructure BP provides various options to assess the national infrastructure. Indonesia can use this for deployment of both large reactors and SMRs, along with the corresponding nuclear fuel cycle facilities (NFCFs). There are URs in the legal and institutional infrastructure, industrial and economic infrastructure, political support and acceptance, availability of human resources, minimization of infrastructure, and the implementation of regional and international arrangements. The regional and international arrangements can support meeting the demand for energy and related products, while reducing the need for investment in national infrastructure. These options should also examine the adequacy of the local infrastructure, including the limited power grid and remote locations of the facility sites. An overview of the INPRO assessment of infrastructure is in Table 2, including the BP, URs, and CRs. There are six URs, with multiple CRs.

Table 2. Overview of Sustainability Assessment in Infrastructure [5]

User Requirement (UR)	Criteria (CR)
Infrastructure BP: *A country shall be able to adopt, maintain or enlarge an NES for the supply of energy and related products without making an excessive investment in national infrastructure*	
UR1: Legal and institutional infrastructure An adequate legal framework should be established to cover issues of nuclear liability, safety and radiation protection, environmental protection, control of operation, waste management and decommissioning, security, and non-proliferation.	**CR1.1: Legal Aspects**
	CR1.2: Institutions
UR2: Industrial and economic infrastructure The industrial and economic infrastructure of a country with an NES should be adequate to support the project throughout the complete lifetime of the nuclear power programme, including planning, construction, operation, decommissioning and related waste management activities.	**CR2.1: Funding of infrastructure**
	CR2.2: Size of nuclear facility
	CR2.3: Siting
	CR2.4: Support infrastructure
	CR2.5: Added value
UR3: Political support and public acceptance Adequate measures should be taken to achieve and maintain public acceptance of an NES being planned or in operation to enable a government policy commitment to support the deployment and operation of the system.	**CR3.1: Public information**
	CR3.2: Public participation
	CR3.3: Survey of public acceptance
	CR3.4: Policy support
	CR3.5: Political environment and investor risk
UR4: Human resources The necessary human resources should be available to enable all responsible parties involved in a nuclear power programme to achieve safe, secure, and economical operation of the NES during its lifetime.	**CR4.1: Human resources**
UR5: Minimization of infrastructure The NES should be designed to minimize the necessary infrastructure for a nuclear power programme.	**CR5.1: Personnel**
	CR5.2: Prefabrication of components
UR6: Regional and international arrangements Regional and international arrangements should provide options that enable a country with an NES to minimize the infrastructure for a nuclear power programme.	**CR6.1: Options to reduce institutional infrastructure**
	CR6.2: Options to reduce industrial infrastructure
	CR6.3: Options to reduce social political infrastructure

The INPRO methodology's basic principle addresses the challenge of building and maintaining a suitable nuclear infrastructure, which has been proven to demand a substantial investment of time and effort, particularly when a country is setting up its first nuclear power plant. This can present a barrier for initiating a nuclear power programme. Therefore, the INPRO methodology aims to ensure that establishing an adequate infrastructure does not impose an undue financial burden on countries intending to start, maintain, or expand a nuclear power programme. [5]

The assessment for SMR and large reactor deployment for infrastructure in Indonesia is given in Figure 4. Indonesia published the large power reactor NESA in 2015. This assessment used the INPRO manual from 2008 [16]. The SMR assessment uses the updated INPRO Manual on Infrastructure, published in 2014 [5]. The new manual has more URs. Figure 4 shows that most of the CRs are met, while two are partially met in each case and one is not met for the SMR NESA. The red box in the figure shows the overlap in the URs for the new manual with the 2008 manual.

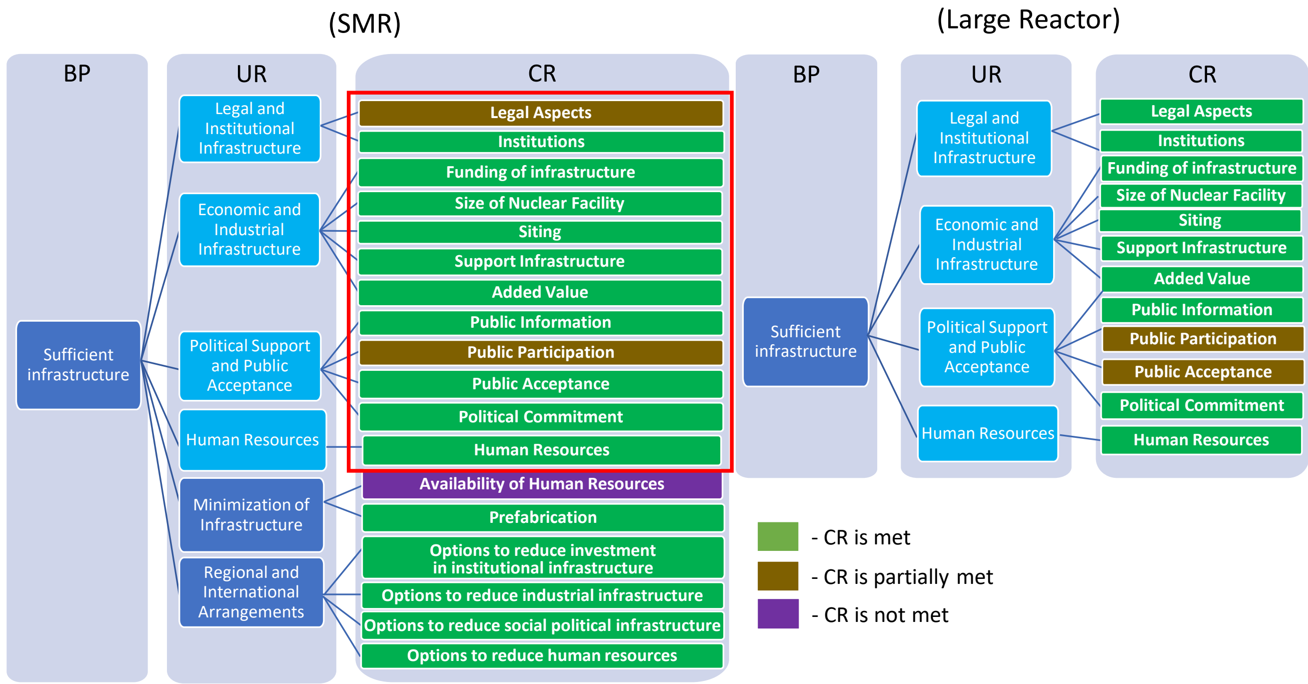

FIG. 4. NESA for SMR and Large NPP deployment in Indonesia in the area of infrastructure. [12, 13]

The infrastructure assessment deployment of SMRs or a large-scale NPP in Indonesia was similar. Below is a detail of some key CR.

Criterion CR1.1 – Legal Aspects

SMR: For SMRs based on LWRs, these regulations are generally applicable. However, for SMRs based on non-LWR technologies, a graded approach must be taken to ensure compliance with regulations; more detailed and specific regulations may need to be developed for these reactor types. CR 1.1 is partially met.

Large NPP: Indonesia has largely adopted IAEA publications as the basis for its regulations on power reactors, with a focus on large scale light water reactors (LWRs). CR 1.1 is fully met.

Criterion CR3.3 – Public Acceptance

SMR and Large NPP: In 2014, BATAN surveyed around 5,000 people from 34 provinces to gauge public support for constructing NPPs in various locations, and found that 72% of respondents were in favor, indicating partial fulfilment of CR3.3. Continuous dissemination of information, stakeholder engagement, and various outreach strategies are needed to build political confidence. A 2019 study in West Kalimantan, a potential location for SMR, showed an 87% acceptance rate. Overall, public acceptance for NPPs has been growing since 2014. Public acceptance is partially met.

Criterion CR5.1 – Availability of Human Resources

SMR and Large NPP: Currently, there is no available information regarding the implementation of automation to reduce operational personnel for the SMR. The main issue is that SMRs are innovative products that are mostly in the design or licensing stage, and only a few are being constructed. At the same time the existing design of a large reactor from the same vendor incorporates this information. CR5.1 is not met for the SMR case. For the large-scale reactor, the CR was not evaluated.

3. Summary

NESAs can be successfully applied to SMR in economics and infrastructure to advanced technology, as shown by Indonesia case study. A NESA using INPRO methodology enables technology holders, designers, and States to pinpoint gaps and weaknesses.

One of the main challenges in the NESA is insufficient data for the assessment. Vendors remain very cautious in providing technical information on their SMRs. Nevertheless, NESA can be carried out successfully, and vendors involvement could be essential to enhance the assessment. The INPRO's NESA can be confidential, to protect data.

For SMRs to be cost competitive does not mean being the cheapest option for electricity generation in a country or region. There are many factors that drive the decision making regarding the choices of energy supply such as suitability for small grids, operating at less than full power, and the desire for reducing reliance on fossil fuel plants to meet net zero emission goals.

INPRO supports decision making in sustainable development of nuclear energy actively. INPRO developed a support package including assessment templates, checklists for data, detailed manuals, and overview of the methodology. INPRO pursued collaborative projects with Member States and SMR vendors in performing limited scope NESAs in economics and safety. These early collaborative projects began in INPRO with SMRs such as CAREM (Argentina), RITM-200N (Russian Federation), SMART (Republic of Korea), and now a joint effort using Seaborg's Compact Molten Salt Reactor for deployment in Viet Nam. INPRO continues to update tools and assessment areas. The INPRO methodology strives to support Member States in achieving sustainable development of innovative NES.

4. ACKNOWLEDGMENTS

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