International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) Methodology for Sustainability Assessment of Nuclear Energy Systems: An Overview

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Abstract
The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was established in 2000 through an International Atomic Energy Agency (IAEA) general council resolution. The INPRO objective is as follows: *Ensure nuclear energy can contribute, in a sustainable manner, to the energy needs of the current century and beyond.* This objective is accomplished through *s*upporting Member States in their planning for sustainable nuclear energy, supporting INPRO methodology self-assessments for advanced and innovative nuclear energy systems, and facilitating cooperation and collaboration among Member States in their respective roles as nuclear energy technology developers, suppliers and customers. INPRO is a comprehensive IAEA forward looking project on the sustainability of nuclear energy. INPRO for sustainability of nuclear energy systems is broken into four main task areas: global scenarios analysis, role of innovations in sustainability, sustainability assessments, and outreach and planning. INPRO developed the nuclear energy system assessment (NESA) for evaluating sustainability over the life cycle of a nuclear energy system. NESA is a holistic methodology compiled in the following 6 assessment areas: environment, safety, economics, waste management, infrastructure, and proliferation resistance (which underwent a recent update). The INPRO methodology is a hierarchical mechanism consisting of basic principles, user requirements, and criterion. The INPRO methodology begins with a basic principle or a sustainability objective in each assessment area. Each basic principle is broken into two or more user requirements. At the foundation of the INPRO methodology, the criteria/ metrics help the assessor verify whether the nuclear energy system meets the user requirements. The NESA is utilized to determine if the criteria are fulfilled, which indicates a sustainable nuclear energy system. If the criteria are not met, technology development/ design may be required to modify the design. For Innovative systems, the NESA can identify areas where research and development is needed to close gaps in sustainability. Recently, INPRO made available a "support package" to provide assistance to Member States with performing NESAs.

Introduction

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) derived its concept of a sustainable development of nuclear energy from the United Nations (U.N.) 1987 Report of the World Commission on Environment and Development: Our Common Future [1]. Sustainable development was defined in the report as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs*"* [1]. The Common Future report stated that the "ultimate limits to global development are perhaps determined by the availability of energy resources and by the biosphere's capacity to absorb the by-products of energy use", illustrating the two-fold issue of supply/resource depletion and emissions/global warming issues [1].

In addition to the economic and environmental factors, societal or political and institutional factors play a role in the sustainable development of energy. Sustainability requires a clear focus on the conservation and efficiency of energy production and usage [1]. Energy system planning is not source specific and takes place on national, regional, and global levels. The energy plan should consider the role of all potential sources, including but not limited to nuclear energy. A methodology for assessing the sustainability of an energy supply must consider the four U.N. sustainable development areas: economics, environment, society, and institutional governance. Keeping in mind the U.N. concept of sustainable development of energy, INPRO developed a methodology for performing a sustainability assessment of nuclear energy systems. The INPRO sustainability assessment of nuclear energy addresses each of the U.N. development areas with six key assessment areas: economics, safety, environmental impact, waste management, proliferation resistance and infrastructure. A nuclear energy system assessment using the INPRO methodology can confirm or deny the sustainability of nuclear energy in a given scenario. The methodology may also be used to identify areas of improvement or gaps to achieve a sustainable nuclear energy system.

What is the INPRO methodology?
INPRO methodology assesses the four U.N. sustainable development areas (Figure 1) against the following goals. (1) Nuclear energy products must be competitive compared to alternative energy sources. (2) Impact of stressors on environment must stay within performance envelope of current nuclear energy systems, while having sufficient resources to run the nuclear energy system ~100 years. (3) Waste must be managed in a manner as to protect the environment and humankind while avoiding undue burdens on future generations. (4) Safety of the nuclear energy system installations should be superior compared against the safety of the reference plants. (5) Future nuclear energy systems must remain unattractive for providing nuclear material for a weapon or nuclear explosive device through a combination of intrinsic features and extrinsic measures. (6) Adequate legal framework and regulatory body to create/maintain nuclear energy systems must be present.

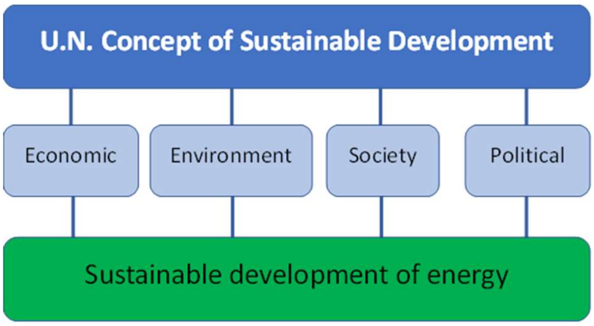

Figure 1: United Nations sustainable development areas

An INPRO assessment covers both evolutionary and innovative designs for nuclear energy systems. An evolutionary design is an advanced design improves upon existing designs through small to moderate modifications, with a strong emphasis on maintaining proven design elements to minimize technological risks. While an "innovative design is an advanced design which incorporates conceptual changes in design approaches or system configuration in comparison with existing practice" [2]. A NESA covers all facilities involved in the entire lifecycle of the nuclear energy system (NES) or the State's nuclear fuel cycle. While a full NESA covers all assessment areas, in cases of innovative NES or component analysis a limited scope NESA covering only select areas can be utilized. The INPRO methodology for nuclear energy system assessment is a comprehensive, internationally agreed upon, criteria-based sustainability assessment, developed through consultancy and technical meetings with Member States and international experts. INPRO methodology was originally published in 2003 with IAEA-TECDOC-1362 [3]. In 2008, the IAEA published “Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual,” IAEA-TECDOC-1575 [4]. This publication included 9 INPRO Manuals: (1) Overview of the Methodology, (2) Economics, (3) Infrastructure, (4) Waste Management, (5) Proliferation Resistance, (6) Physical Protection, (7) Environmental, (8) Safety of Nuclear Reactors, and (9) Safety of Nuclear Fuel Cycle Facilities. INPRO began updating the INPRO manuals in 2014 and have recently released a “support package” to Member States to provide assistance in preforming NESAs.

What is the framework for the INPRO methodology?

The INPRO methodology uses a hierarchical approach beginning with the assessment goals previously described (Figure 2). The goals are utilized to develop fundamental basic principles (BP) for each assessment area. A BP is a statement of the general goal that must be achieved in a NES for it to be sustainable in the long term. User requirements (URs) and criteria (CR) are utilized to determine if the BP is met. A UR defines conditions that much be achieved to fulfil the basic principle (BP). The UR is for specific institutions (users) involved in nuclear energy development, deployment, and operation. A *criterion* enables the assessor to qualify a UR for a given NES. In order to simplify the assessment process CRs may have associated evaluation parameters. Each assessment area is made up of a singular BP containing 2-7 UR, while each UR consists of 1-6 CR.

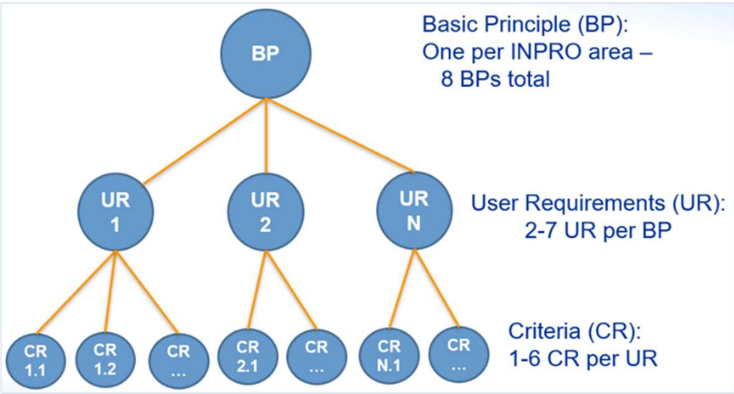

Figure 2: INPRO methodology framework

What is a nuclear energy system assessment?

A nuclear energy system assessment (NESA) is a process used for self-assessing the long-term sustainability of an NES or NES component. The evaluation takes place at the CR level of the sustainability assessment. Each CR consists of one or more indicators (IN) and their corresponding acceptance limits (AL) (Figure 3).

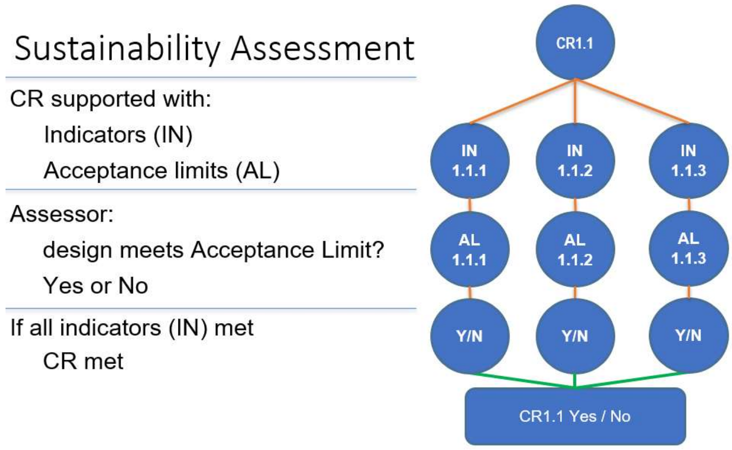

Figure 3: Evaluation process of a criterion

The IN and AL are used to make a judgement of acceptability of the CR. IN and AL may be logical or quantitative (pass/fail) or qualitative (better/poorer) [5]. When a IN and its corresponding AL are in agreement the CR is met (Figure 4). When a CR is not met, it identifies a gap; the designer/State can modify the NES design to achieve sustainability. After modifying the design, the NES can be revaluated to see if it meets the CR. This process is similar to the safeguards/security/safety by design concept. Sometimes when CR are not met, it identifies an area of need for research and development to close the gap, which is commonly the case for innovative systems. Following this approach outlined in Figure 2, when all the CRs for a UR are met, then the UR is met. Similarly, when all the UR are met, the BP is fulfilled and thus the NES is sustainable.

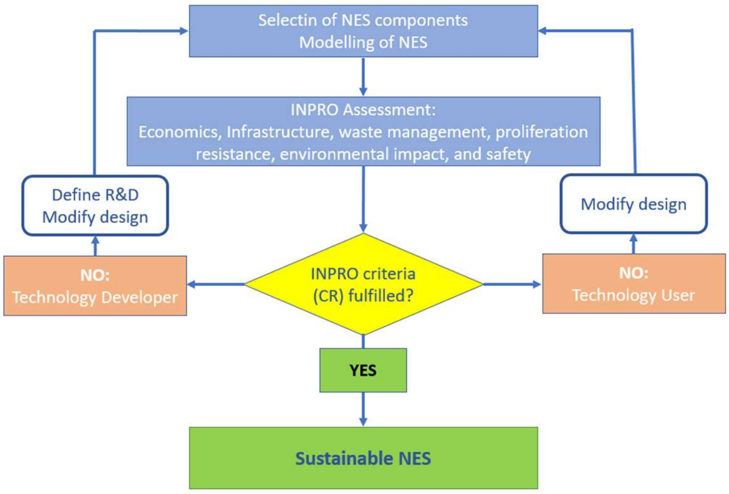

Figure 4: CR fulfillment flowchart

What are the areas and basic principles in NESA?

NESA being a holistic assessment is compiled of six areas: economics, environment, waste management, safety, proliferation resistance, and infrastructure. Further guidance on the assessment areas and process for performing an assessment are in their corresponding manuals. Countries complete energy planning studies to assess how nuclear energy fits into their energy supply portfolio. These studies define the NES for the INPRO assessment.

Economics

Economically a NES must be available, affordable, and competitive with other energy sources. The INPRO assessment of economics provides an independent assessment of the economics of the NES [6]. Nuclear energy does not need to be the cheapest source of energy, but it must be competitive. Factors considered when determining a countries or regions energy sources include but are not limited to the security of energy supply, long term stability in energy costs, diversity of energy supply technologies, degree of interest for industrial development, and domestic resources present.

Such considerations are usually taken into account in energy planning studies and may lead decision makers and investors to accept a slightly higher cost for one source over another [6]. The attractiveness of investing in nuclear energy is assessed by performing a financial analysis. To be attractive, the cost of energy or electricity supplied by an NES should be comparable with the production costs of alternative supply options available [6]. According to the economical BP, "products and services from nuclear energy systems shall be affordable and available" Figure 5 illustrates the economical BP with its corresponding UR.

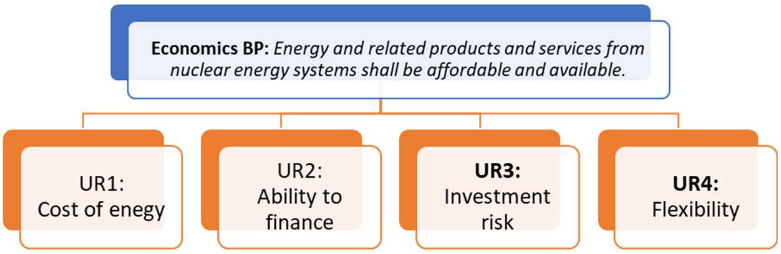

Figure 5: Economical BP and URs for an INPRO NESA

Environmental Impact

Protection of the environment is essential to the concept of sustainable development. Nuclear power supports sustainable development by providing energy with limited burden on the atmosphere, water, and land. The introduction of NES also helps to alleviate some of the environmental burden brought on by other forms of energy production, such as the burning of fossil fuels. The environment assessment area is comprised of two concepts the environmental impact from stressors (Figure 6) [7] and the environmental impact from depletion of resources (Figure 7) [8].

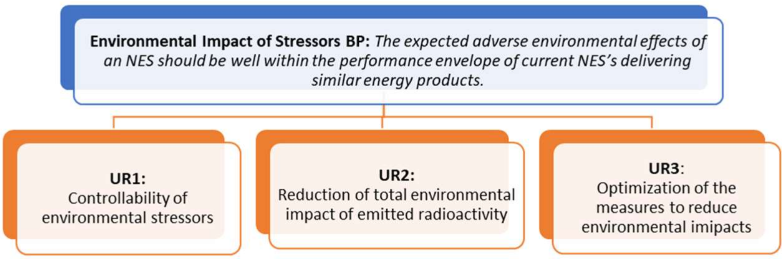

Figure 6: The environmental impact of stressors BP and URs for an INPRO NESA

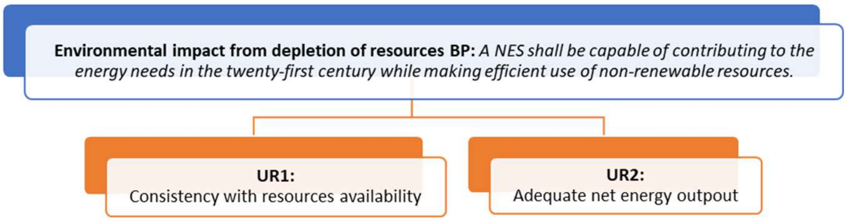

Figure 7: The environmental impact from depletion of resources BP and URs for an INPRO NESA

In order to have a holistic account of the environmental effects, factors such as the physical, chemical, or biological changes in the environment, health effects on people, plants, and animals, and the use/ depletion of resources must be considered.

Waste Management

The management of radioactive waste must be handled in a manner that does not impose undue burdens on future generations [9]. In order to ensure the proper waste management, the following requirements must be met (Figure 8). Minimal waste generation at the lowest classification possible at all stages of the NES. Intermediate steps between generation of the waste and the end state are taken as early as reasonably practicable and are not to inhibit or complicate the achievement of the end state. An achievable end state that provides permanent safety without further modification is specified for each class of waste.

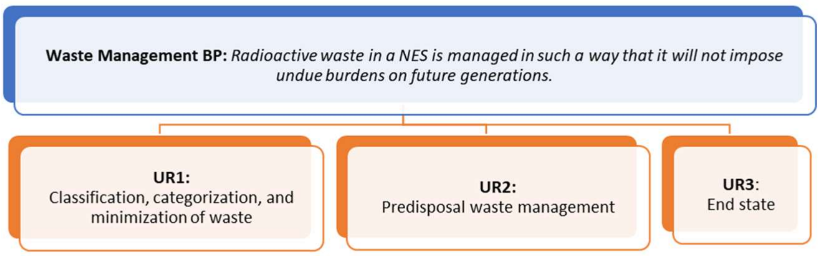

Figure 8: The waste management BP and URs for an INPRO NESA

Safety

The fundamental safety principles can be divided into the key factors for nuclear reactors and for fuel cycles. Nuclear reactors are dependent on the factors of reactivity control, heat removal from the core, radioactive materials, and shield radiation [10]. While, fuel cycle safety principles are dependent on criticality control, decay heat removal from radionuclides, radioactivity confinement, and radiation shielding [11]. INPRO expects that NES will incorporate inherent and passive safety features in order to prevent, reduce, and contain radioactive releases. Safety analyses will involve a combination of deterministic and probabilistic assessments and vary slightly depending on the type of NES or NES component.

Proliferation Resistance

When designing and implementing NESs, it is pertinent to consider the potential misuse as pertaining to nuclear weapons and nuclear explosive devices. NESAs provide guidance on incorporating proliferation resistance through a combination of intrinsic features and extrinsic measures into NES as required in the proliferation resistance BP (Figure 9). This manual was the last manual updated in the INPRO methodology. The following reflects the BP/UR in the updated manual.

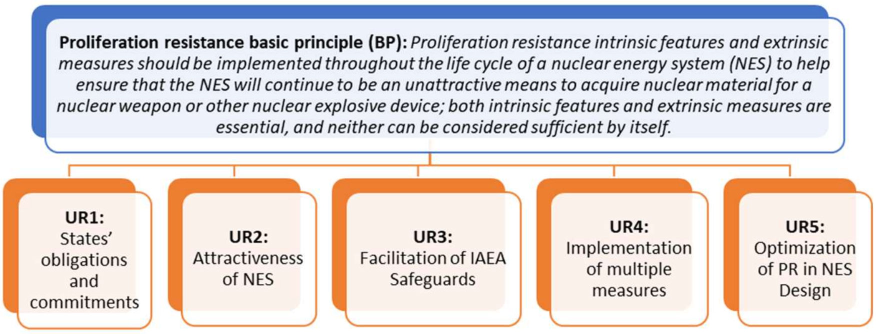

Figure 9: The proliferation resistance BP and URs for an INPRO NESA

Intrinsic features consist of technical features that: reduce the attractiveness of nuclear material for nuclear weapons; prevent or inhibit the diversion of nuclear material; prevent or inhibit the undeclared production of direct-use material; and that facilitate nuclear material accounting and verification [12]. Extrinsic measures are based on a States' decisions andundertakings related to nuclear energy systems and fall into one of five different categories: commitments, obligations and policies of states; agreements between exporting and importing states on exclusive use of nuclear energy systems for agreed purposes; commercial, legal or institutional arrangements that control access to nuclear material and technology; verification measures by the IAEA or by regional, bilateral and national measures; and legal and institutional measures to address violations of measures defined above [12]. The proliferation resistance basic principle requires that proliferation resistance features and measures be implemented throughout the full life cycle of a NES. This proliferation resistance assessment only evaluates declared nuclear material and facilities.

Infrastructure

Nuclear power infrastructure comprises all features and substructures that are necessary for the successful deployment and operation of nuclear power plants including legal, institutional, industrial, economic, social features and substructures. Infrastructure is the collection of necessary capabilities of national institutions to achieve long term sustainability of an NES. This methodology area defines a series of measures that national institutions should take such as the establishment of a legal framework, the selection of an appropriate site/ location, and national nuclear industry support [13]. In order to have a sufficient infrastructure for an NES there must be a public acceptance of the nuclear power programme as well as the necessary human resources to establish and maintain the nuclear programme. Additionally, the methodology addresses measures that a designer and the State may take to reduce the necessary effort to establish and maintain a nuclear infrastructure [13]. Establishing and maintaining an adequate nuclear infrastructure requires a significant investment of time and effort and holds the potential to be a barrier for the implementation of an NES. The infrastructure BP (Figure

10) states that the establishment of a sustainable infrastructure shall not require an excessive investment from the country during implementation, maintenance, or expansion of an NES.

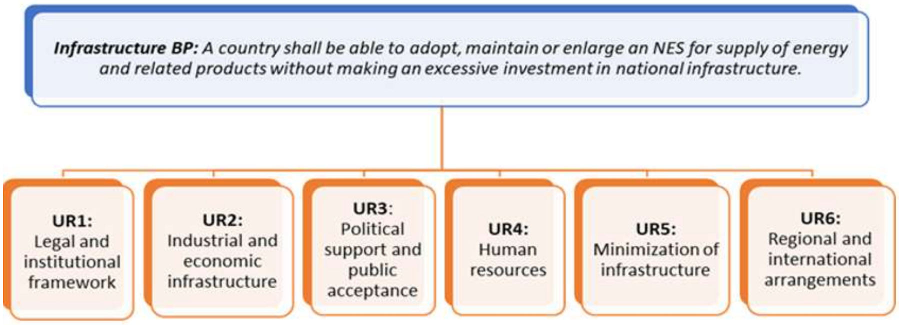

Figure 10: The infrastructure BP and URs for an INPRO NESA

To minimize the effort needed in the nuclear infrastructure, the designer should optimize the design in order to reduce the human resources required to operate the nuclear facility. A State should also utilize all available international and regional arrangements to limit the burden of infrastructure.

Performing a NESA

There are typically three types of NESA users: nuclear technology developers, experienced technology users, and newcomer countries [5]. Nuclear technology developers and newcomer countries tend to do a limited scope NESA while, experienced technology users typically may do a full scope NESA. The steps in preforming a NESA are illustrated below in Figure 11. There are INPRO manuals to cover all areas of assessment, and INPRO is available to provide support through the process, and with trainings or briefings.

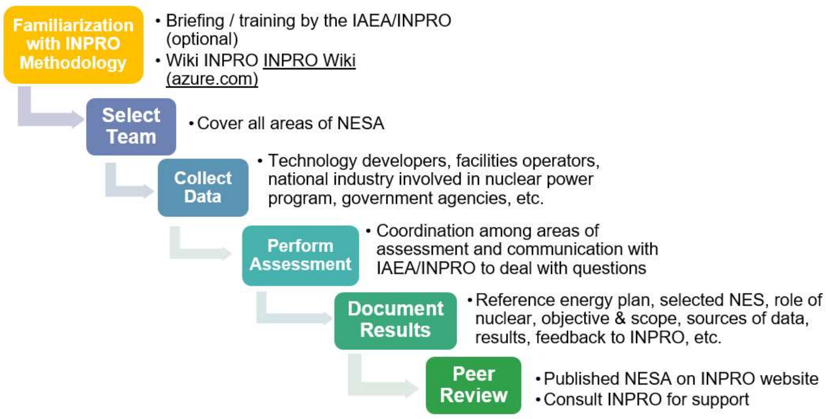

Figure 11: Steps in preforming an INPRO NESA

The time required for an INPRO NESA and its documentation depends on the decided scope and team of experts involved. Full scope NESA covering all methodology areas and a State's full NES with cooperation of technology developers and State could take approximately 2 years. However, limited scope NESAs can take 6-12 months, depending on team, level of detail in the design, and assessment areas. Limited scope NESAs are often completed early in the design stage to identify any gaps in sustainability. The publication of the NESA is not required, though recommended to enhance the communal knowledge of NES. When publishing the Member State or assessor has the option to withhold some or all of the details regarding the NES, specifically the design.

Summary

Since it was established in 2000, INPRO has worked to "Ensure nuclear energy can contribute, in a sustainable manner, to the energy needs of the current century and beyond" [1?]. This is accomplished through the continuous support of Member States in their planning for sustainable nuclear energy, the application of INPRO methodology self-assessments for advanced and innovative nuclear energy systems, and the facilitation of cooperation and collaboration among Member States. To evaluate the sustainability of a nuclear energy system over the entirety of its life cycle, INPRO developed the nuclear energy system assessment (NESA). NESA, a holistic methodology, compiled of 6 assessment areas: environment, safety, economics, waste management, infrastructure, and proliferation resistance. The INPRO methodology is a hierarchical mechanism beginning with a basic principle or a sustainability objective in each assessment area to establish a goal that should be met in order to achieve long term sustainability. Each basic principle is broken into two or more user requirements that would need to be met in order to satisfy the basic principle. At the foundation of the INPRO methodology, the criteria/metrics help the assessor verify whether the nuclear energy system meets the user requirements. The ultimate goal of the application of the INPRO methodology is to confirm that the NES assessed fulfils all the CR and hence the user requirements (URs) and basic principles (BPs) and therefore represents a long-term sustainable system for a Member State (or group of Member States). If the criteria are not met, the NESA can identify areas where the design needs modification or there is a need for research and development to close gaps in sustainability. Given the holistic nature of the INPRO assessment, Member States, including designers and users, can use the methodology for long term planning of sustainable nuclear energy systems.

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