IAEA Nuclear Energy Series

No. NG-T-4.4

Basic Principles

Objectives

Guides

Technical Reports

INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Economics

INPRO Manual

IAEA

International Atomic Energy Agency

IAEA NUCLEAR ENERGY SERIES PUBLICATIONS

STRUCTURE OF THE IAEA NUCLEAR ENERGY SERIES

Under the terms of Articles III.A and VIII.C of its Statute, the IAEA is authorized to foster the exchange of scientific and technical information on the peaceful uses of atomic energy. The publications in the **IAEA Nuclear Energy Series** provide information in the areas of nuclear power, nuclear fuel cycle, radioactive waste management and decommissioning, and on general issues that are relevant to all of the above mentioned areas. The structure of the IAEA Nuclear Energy Series comprises three levels: **1 — Basic Principles and Objectives**; **2 — Guides**; and **3 — Technical Reports**.

The **Nuclear Energy Basic Principles** publication describes the rationale and vision for the peaceful uses of nuclear energy.

Nuclear Energy Series Objectives publications explain the expectations to be met in various areas at different stages of implementation.

Nuclear Energy Series Guides provide high level guidance on how to achieve the objectives related to the various topics and areas involving the peaceful uses of nuclear energy.

Nuclear Energy Series Technical Reports provide additional, more detailed information on activities related to the various areas dealt with in the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series publications are coded as follows: **NG** — general; **NP** — nuclear power; **NF** — nuclear fuel; **NW** — radioactive waste management and decommissioning. In addition, the publications are available in English on the IAEA Internet site:

http://www.iaea.org/Publications/index.html

For further information, please contact the IAEA at PO Box 100, Vienna International Centre, 1400 Vienna, Austria.

All users of the IAEA Nuclear Energy Series publications are invited to inform the IAEA of experience in their use for the purpose of ensuring that they continue to meet user needs. Information may be provided via the IAEA Internet site, by post, at the address given above, or by email to Official.Mail@iaea.org.

INPRO METHODOLOGY FOR SUSTAINABILITY ASSESSMENT OF NUCLEAR ENERGY SYSTEMS: ECONOMICS

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWAZILAND
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

IAEA NUCLEAR ENERGY SERIES NO. NG-T-4.4

INPRO METHODOLOGY FOR SUSTAINABILITY ASSESSMENT OF NUCLEAR ENERGY SYSTEMS: ECONOMICS

INPRO MANUAL

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2014

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

Printed by the IAEA in Austria
August 2014
STI/PUB/1653

IAEA Library Cataloguing in Publication Data

INPRO methodology for sustainability assessment of nuclear energy systems : economics. — Vienna : International Atomic Energy Agency, 2014.
p. ; 30 cm. — (IAEA nuclear energy series, ISSN 1995–7807 ; no. NG-T-4.4)
STI/PUB/1653
ISBN 978–92–0–102714–6
Includes bibliographical references.

1. Nuclear energy — Economic aspects. 2. Nuclear energy — International cooperation. 3. Nuclear energy — Evaluation. 4. International Project on Innovative Nuclear Reactors and Fuel Cycles. I. International Atomic Energy Agency. II. Series.

IAEAL 14–00920

FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was launched in 2000, based on resolutions of the IAEA General Conference (GC(44)/RES/21). One of the INPRO objectives is to help to ensure that nuclear energy is available in the 21st century in a sustainable manner. To meet this objective, INPRO is proceeding in steps. In its first step, referred to as Phase 1, INPRO developed a set of basic principles, user requirements and criteria, together with an assessment method which, taken together, constitute the INPRO methodology, for the evaluation of a national or global nuclear energy system in regard of its long term sustainability. The methodology was documented in the form of an assessment manual and comprised an overview and eight volumes covering the areas of economics, infrastructure, waste management, proliferation resistance, physical protection, environment, safety of reactors and safety of nuclear fuel cycle facilities. The first edition of this manual was published in 2008 as IAEA-TECDOC-1575 Rev. 1.

In its second step, referred to as Phase 2, INPRO Member States are performing national and international nuclear energy system assessments (NESAs) using the INPRO methodology. The results of the NESAs conducted up to 2009 were documented in IAEA-TECDOC-1636, published at the end of 2009. This publication includes several proposals on how to update the INPRO methodology, based on the experience of the assessors. In parallel, the INPRO steering committee, IAEA experts and the INPRO group also developed recommendations on how to update the methodology.

All proposals and recommendations were evaluated by internal and external experts in an IAEA consultants meeting in 2012. The INPRO Manual was updated on the basis of the discussions at this meeting. This report covers the area of economics of the INPRO methodology.

The IAEA officers responsible for this publication were A. Korinny and J. Phillips of the Division of Nuclear Power.

CONTENTS

SUMMARY

This report, which is part of the INPRO Manual, provides guidance on assessing a nuclear energy system (NES) in the area of economics. For a NES to be sustainable in the long term, nuclear energy needs to be available and to be affordable. If nuclear energy is to be available, utilities must be prepared to invest in the deployment of nuclear power plants (NPPs) for the supply of energy, today, primarily the supply of electricity. So, within the area of economics the attractiveness of investing in nuclear power is assessed by evaluating financial figures of merit, such as return on investment (ROI) and the internal rate of return (IRR), to ensure that they are comparable with those expected from investing in alternative sources of energy or electricity supply. The potential risks of investment in an NPP also need to be assessed. To be affordable, the cost of energy or electricity supplied by an NPP should be comparable with the production costs of alternative supply options available in a given market, taking into account all relevant costs.

In other words, nuclear power must be competitive with other energy supply options. Achieving competitiveness is primarily a task for the designer, but a country considering whether to construct a first, or additional, NPP(s) needs to determine whether nuclear power is competitive with alternatives, taking into account economic conditions in the country. Note that in the INPRO methodology area of economics, it is the cost of energy from the NPP that is considered and compared with the costs of other supply options. The costs of the other components of a NES, such as front end facilities that are required for the supply of fuel and back end facilities and activities such as decommissioning and waste disposal, are factored into the cost of the energy from the NPP.

In general, when considering the use of nuclear power, energy planning studies will be carried out at an early stage to see how nuclear power will fit into a country`s energy supply portfolio. The overall objective of such studies is to determine whether nuclear power has a role in an optimized energy supply portfolio, taking into account a variety of considerations such as security of supply, capital investment requirements, availability of domestic energy sources, etc. An assessment in the INPRO area of economics provides an independent assessment of the economic competitiveness of nuclear power, compared with available alternatives.

In the INPRO methodology area of economics, there is one basic principle, four user requirements, and eight criteria. The goal of the basic principle has already been introduced, namely that energy and related products and services from NESs shall be affordable and available.

The first user requirement states that the cost of energy products (C_N) from a NES, taking all relevant costs and credits into account, should be competitive with that of alternative energy sources (C_A) that are available for a given application in the same time frame and geographical region. In comparing costs, the INPRO methodology uses the concept of discounted costs (levelized unit energy costs (LUEC)) for comparing the costs of electricity produced by nuclear and by available alternative energy sources. There are a variety of approaches to calculating LUEC but, by definition, the LUEC is 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. The discount rate used in calculating the LUEC needs to reflect market conditions in the relevant jurisdiction.

The assessor is asked to compare the LUEC for C_N with those for alternatives, C_A. The assessor may or may not perform the actual calculation, but the assessor needs to be confident that all costs have been included in the calculations, that they are realistic, and that parameters that are used such as load factor and discount rate, are appropriate. Assessors can use a tool, NEST (NESA economic support tool), available from the IAEA and described in Appendix II of this publication, to calculate C_N and C_A should they so desire.

To be cost competitive does not mean nuclear power must be the cheapest option for electricity generation in a country. In a given country or region, many factors can enter into the decision making process regarding the choice(s) of energy supply. For example, these include: considerations of security of energy supply, long term stability in energy costs and diversity of energy supply technologies, i.e. the energy mix of both the market as a whole and of the given producer/supplier; the desire for industrial development and the role nuclear technology can play in such development; judgments about environmental impacts, either positive or negative, avoided emissions, safety, sustainability, waste management; utilization of domestic resources, such as mineral and labour resources and industrial capacity; and public and hence political acceptance. Such considerations are usually taken into account in energy planning studies, as mentioned above, and may lead decision makers and investors, particularly governments, to accept a somewhat higher cost for the nuclear option compared with an alternative energy source.

The second user requirement asks that the total investment required to design, construct and commission NESs, including interest during construction, should be such that the necessary investment funds can be raised (in the country). Constructing an NPP is a large scale capital project that will be implemented over many years, typically ten years or more, starting with pre-project planning, and one that requires a high front end investment of several billions of dollars. Thus, raising the necessary funds can be a major challenge. Two criteria need to be satisfied. In the first instance investing in the construction of an NPP needs to be sufficiently attractive to justify doing so. The assessor is asked to examine the relevant financial figures of merit used to in a given jurisdiction/market to characterize the 'profitability' of such an investment to determine whether the financial figures of merit are comparable with those for an investment in alternative energy/electricity supply options. Regardless of the attractiveness of the financial figures of merit, it must also be possible to raise the total investment required, i.e. the total investment needs to be compatible with the ability to raise capital in a given market.

Investors can look at a variety of financial indicators when evaluating the attractiveness of investments including IRR, the closely related indicator of net present value (NPV) of cash flows, the payback period, ROI, etc. These financial figures of merit used in a given region will reflect the investment climate and requirements of a given country or region, including the source(s) of investment funds. In some countries or regions, a NES will require private sector investment, while in other countries or regions a NES may require government investment or guarantees. Private sector investors will be attracted by a competitive IRR, provided the IRR is commensurate with their judgment of associated risks (discussed further below).

As noted, the NPV of cash flows and IRR are closely related and are calculated using the concept of levelized value of money, but NPV analysis may facilitate taking into account other benefits, such as security of energy supply and technology development, that may be of more interest to government investors than private sector investors. ROI — a non-levelized parameter — may be attractive as an indicator complementary to IRR and NPV.

Values of the financial figures of merit chosen for a given NES should be attractive compared with investments in competing energy technologies. Thus, they should be at least comparable to the values for competitive energy sources, and preferably better. The NEST code can be used to calculate these values.

An acceptable 'size' of investment will vary with time and region and will depend on many factors such as available sources of investment, the overall state of the economy of a given region/country, the size of the investment relative to a utility's annual cash flow (and hence the size of the unit relative to the size of the grid), and the size of the investment compared with that needed for alternative sources of supply that make up a balanced supply portfolio.

In the end, the investment to deploy a NES must be affordable and attractive in a given investment climate, taking into account other investment options and other priorities requiring a share of available capital. The assessor is asked to confirm that the investment in an installation of a NES is sufficiently attractive to a potential investor compared with an investment in an alternative energy system available in the country assessed and that the investor (e.g. the future operator of the NES) is capable of raising the needed capital.

The third user requirement states that the risk of investment in a NES should be acceptable to investors. As already mentioned, construction of an NPP is a large scale capital project that is implemented over a long time frame. In the past, some projects have experienced large cost overruns and some plants have not operated as well as anticipated. Thus, potential investors will want reasonable assurances that the 'profitability' of their investment will not be unduly compromised because of shortcomings in project implementation nor by shortcomings in plant performance.

Investor risk related to an installation of a NES comprises several factors, including among others, uncertainties in basic project cost, the cost of project delays, regulatory uncertainties that may impact either the project schedule or the plant performance or both, the impact of adverse public pressure, and technical issues that lead to shortfalls in plant operation. Regulatory and technical uncertainties represent a project cost and schedule risk and a risk that the plant will not operate with the load factor assumed in the financial analysis. Regulatory uncertainties are linked to technical maturity, and so in the INPRO methodology the two are considered together. The assessor is asked to confirm that the technical development and the licensing status of a plant to be deployed (or developed) are both adequately mature. Four different situations are considered: deployment of the first few NPPs in a country, deployment of additional units of the same basic type of NPP, deployment of a new type of plant, i.e. first of a kind (FOAK) in a country with experience operating NPPs, and technology development.

Project delays lead to cost overruns, particularly in project management and engineering support costs and in interest during construction. Thus, the time taken to construct new facilities and to bring them into operation (and so to start to generate revenue) should be as short as practicable, but it is important to ensure that the economic analyses used to calculate LUEC and financial figures of merit are based on a schedule that is realistic and, ideally, similar to that which has been achieved in past construction projects for plants of the same or similar basic design. So, the assessor is asked to confirm that the project schedule (times for construction and commissioning) used in the economic analyses are sufficiently accurate, i.e. that the schedule is realistic and not unduly optimistic. Again four different situations are considered: deployment of the first few NPPs in a country, deployment of additional units of the same basic type of NPP, deployment of a new type of plant, i.e. first of a kind (FOAK) in a country with experience operating NPPs, and technology development.

In addition, the assessor should have available the results of a sensitivity analysis that tests the impact of changes in the values of important input (economic) parameters — such as overnight construction cost, discount rate, length of construction time, plant load factor — on the economic evaluation, i.e. the values of C_N and C_A and financial figures of merit. The assessor is asked to review such a sensitivity analysis to identify the range over which these important input can vary, such that the nuclear project remains competitive and attractive compared with alternative energy projects in the country. The assessor may or may not carry out the analysis, but should the assessor decide to do so he may use NEST, described in Appendix II.

Finally, the assessor is asked to consider the ‘political climate’ or environment in the country to determine whether there is sufficient political support for nuclear power and whether such support is likely to be sustained. This information on the political climate is needed for an assessment in the INPRO methodology area of infrastructure. The issue of the political climate is mentioned in the area of economics primarily to ensure that such an assessment in the area of infrastructure has been carried out and that this assessment has established that the political climate is favourable. If such an assessment has not been done, the assessor in the area of economics should conclude that the investor is faced with an unknown and important risk that needs to be addressed by the proponent of the project. It is not the responsibility of an economic assessor to judge the political climate, but rather to ascertain that the issue has been addressed.

The fourth user requirement asks that innovative NESs should be compatible in meeting the requirements of different markets. This user requirement is directed primarily at technology developers and relates to the ability to recover the development investment.

Given the uncertainty about the future, ideally, innovative NESs should be sufficiently flexible to be able to evolve and adapt in a manner that provides competitive energy for as wide a range of plausible futures and markets as possible. So, in deciding whether to develop an innovative NES, or a NES component, the developer would examine whether and how that component might be adapted to different markets or changing market conditions, recognizing, for example, that a given design of reactor would not be expected to meet the needs of all markets. Adaptation of an innovative NES, for example to accommodate different sized modules, or to accommodate different fuels, would usually require additional investment. So, the more markets that a given component could sell into, with only relatively minor changes, the greater would be the attractiveness of developing the component and the greater would be the expected contribution that the component could make meeting the global energy needs of the 21st century in a sustainable manner, the principle objective of INPRO.

While it is easy to ask for such flexibility, there can be inherent limitations that need to be taken into account. For example, designing and licensing a reactor is a costly exercise and changing the design to modify its output is neither simple nor cheap. To date, economies of scale have resulted in larger and larger sized units being designed and developed to the state of being commercially available. Such units are not suitable for small grids and operating them at less than full power does not make economic sense. So, various developers are looking at smaller modular units which, if brought to the state of proven technology, will offer a considerable degree of flexibility.

Designers of larger units, however, can consider other degrees of flexibility to adapt to a changing world. One such example is the ability to accommodate different fuels, e.g. higher burnup fuels, MOX fuels, recycling of uranium (RU) from reprocessing LWR fuel in CANDU reactors. Much has already been done in this area. Also, when designing new fuel cycle facilities there may be more flexibility in adopting modular construction techniques to offer the ability to increase production capacity in a staged manner or to adapt the facilities to the production/reprocessing of different fuel types.

The assessor, who, in this case, is assumed to be a technology developer, is asked to determine that flexibility has been taken into account in the design of the innovative NES.

While the economic assessment is focused on the deployment of NPPs, the methodology can be adapted to look at deployment of other facilities that make up a NES such as front end fuel cycle facilities.

In summary, if nuclear power is to be available and economically attractive and competitive for use in a balanced portfolio of energy supply, it should be able to compete with alternative energy sources in the country (or region or globally) on the production cost of energy/electricity, it should represent an attractive investment, the risks associated with deploying nuclear power should be acceptable, and NESs under development should have flexibility to evolve and adapt in a manner that provides competitive energy for as wide a range of plausible futures and markets as possible.

1. INTRODUCTION

1.1. BACKGROUND

This publication is an update of Volume 2 of the IAEA report Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems INPRO Manual — Overview of the Methodology (IAEA-TECDOC-1575 Rev.1) [1][1] in the area of economics based on recommendations presented by INPRO Member States, IAEA experts and the IAEA–INPRO group.

As noted in the updated INPRO Manual, applying the INPRO methodology in an assessment is a bottom-up exercise and consists of determining the value of each of the INPRO indicators (of a criterion) and comparing the value with the corresponding acceptance limit of the given criterion. Based on the comparison, a judgment on the potential, i.e. the capability of a nuclear energy system (NES) to comply with the criterion is derived.

The ultimate goal of the application of the INPRO methodology is to confirm that the NES assessed fulfills all the criteria, and hence the user requirements and basic principles, and therefore represents a long term, sustainable system for a Member State (or group of Member States). Basic principles, user requirements and criteria have been defined in different areas — economics, legal and institutional measures (infrastructure), waste management, proliferation resistance, physical protection, environmental impact of stressors, availability of resources, and risk reduction by design of nuclear reactors and fuel cycle facilities (nuclear safety).

One possible output from an assessment is the identification of areas where a given NES needs to be improved. Given the comprehensive nature of an assessment using the INPRO methodology, such an assessment would be expected to indicate clearly the specific attributes of a NES that need to be improved and so, could be an important input in identifying necessary or desirable research, development and demonstration (RD&D) objectives.

1.2. OBJECTIVE

The goal of this publication is to provide guidance for performing an assessment, as described in the introductory volume of the updated INPRO manual, in the area of economics. The manual is not intended to provide guidance on how to design a NES to meet the INPRO methodology requirements in the area of economics. Rather, the focus is on the assessment method and the evaluation of the criteria in the area of economics.

The assessor, i.e. the individual or team of individuals carrying out a nuclear energy system assessment (NESA), is assumed to be knowledgeable in the area of economics and financial analysis.

An assessment using the INPRO methodology will either confirm that the economic criteria are fulfilled, and hence that the NES is competitive with alternative energy sources in the country assessed or will result in the identification of shortcomings (gaps or non-compliance with criteria) requiring actions, e.g. changing some of the facilities of the NES such as the reactor, or to defining an RD&D programme to improve the economic performance of the NES to bring it into compliance.

However, in a situation where energy system planning has been performed prior to undertaking the INPRO assessment and a role for nuclear power as part of a balanced energy portfolio has been identified, the follow-on economic assessment using the INPRO methodology would still be valuable. As discussed further in Section 2, in such a case the INPRO assessment results provide additional information through a study of the sensitivity of important economic parameters and added transparency of the economic results.

An economic assessment using the INPRO methodology could be performed by a variety of assessors, such as government planning departments, academic institutions, international agencies, utilities (private or public) or nuclear technology designers (developers) to understand the economic competitiveness of nuclear power compared with alternative sources of energy. The report contains a general discussion of the INPRO methodology requirements in the area of economics as set out in Table 1, and provides guidance on determining the value of the indicators in the area of economics, and on specifying the associated acceptance limits.

---

[1] An update of this publication is in preparation.

While it is assumed that the assessor is knowledgeable in the area of economics, this volume of the INPRO Manual has been written so that a non-expert can understand the INPRO methodology requirements in the area of economics and, hence, the results obtained from a NESA in this area.

1.3. STRUCTURE

In Section 2, a short description of the goals and output of an energy system planning study is presented. Such a study is defined as a prerequisite for a NESA.

General background information on performing an INPRO economic assessment, and the inputs that are needed to perform an assessment, is discussed in Section 3.

A discussion of the basic principle, the associated user requirements and criteria is presented in Section 4. It is important to note that an assessor, i.e. a given Member State may choose other specific criteria (and even user requirements) that reflect its national circumstances. Thus, the information presented in Section 4 is to be considered to be guidance and not a prescription.

In Appendix I, several basic economic terms are discussed in more detail. Appendix II provides a description of the EXCEL based code NEST (Nuclear Economics Support Tool), which includes a methodology for calculating generation costs and financial figures of merit needed to perform an assessment in the area of economics, without using complex computer codes. In addition to the approach proposed by INPRO, models based on studies published by Harvard University [2] and the Massachusetts Institute of Technology [3] are presented. Appendix III lists a numerical example of the input and the output for the models available in NEST. Appendix IV presents a discussion of issues related to the economic aspects of the development of a NES. The requirements presented in the INPRO methodology in the area of economics are set out in Table 1.

TABLE 1. OVERVIEW OF THE INPRO METHODOLOGY IN THE AREA OF ECONOMICS

INPRO Economic Basic Principle (BP):
Energy and related products and services from nuclear energy systems shall be affordable and available.

User Requirement (UR)	Criterion	Indicator (IN) and acceptance limit (AL)
UR1: (Cost of energy): The cost of energy supplied by nuclear energy systems, taking all relevant costs and credits into account, CN, should be competitive with that of alternative energy sources, CA. that are available for a given application in the same time frame and geographic region/jurisdiction	CR1.1: Cost competitiveness	IN1.1: Cost of energy. AL1.1: $C_N \leq k*C_A$ (C_N = cost of nuclear energy, and C_A = cost of energy from alternative source; factor k is usually ≥ 1 and is based on strategic considerations)
UR2: (Ability to finance): The total investment required to design, construct, and commission nuclear energy systems, including interest during construction, should be such that the necessary investment funds can be raised	CR2.1: Attractiveness of investment	IN2.1: Financial figures of merit. AL2.1: Figures of merit for investing in a NES are comparable with or better than those for competing energy technologies
	CR2.2: Investment limit	IN2.2: Total investment. AL2.2: The total investment required should be compatible with the ability to raise capital in a given market climate

TABLE 1. OVERVIEW OF THE INPRO METHODOLOGY IN THE AREA OF ECONOMICS (cont.)

UR3: (Investment risk): The risk of investment in nuclear energy systems should be acceptable to investors	CR3.1: Maturity of design	IN3.1: Technical and regulatory status AL3.1: Technical development and status of licensing of a design to be installed or developed are sufficiently mature
	CR3.2: Construction schedule	IN3.2: Project construction and commissioning times used in economic evaluation AL3.2: Times for construction and commissioning used in economic evaluation are sufficiently accurate, i.e. realistic and not optimistic
	CR3.3: Uncertainty of economic input parameters	IN3.3: A sensitivity analysis of important input parameters for calculating costs and financial figures of merit has been performed AL3.3: Sensitivity to changes in selected parameters is acceptable to investor
	CR3.4: Political environment	IN3.4: Long term commitment to nuclear option AL3.4: Commitment sufficient to enable a return on investment
UR4: (Flexibility): Innovative nuclear energy systems should be compatible with meeting the requirements of different markets	CR4.1: Flexibility	IN4.1: Are the innovative NES components adaptable to different markets? AL4.1: Yes

2. ENERGY SYSTEM PLANNING AND THE ROLE OF NUCLEAR POWER

As described in Ref. [4], an energy system planning study (or energy scenario), which sets out the anticipated growth of energy demand as a function of time and which identifies the available energy supply options and the role of a NES in meeting the energy demand projection, is required.

Generating the electricity and distributing it to customers is complex. A given electrical grid will be fed by a range of generating sources, which usually will include some combination of hydropower, a variety of fossil and nuclear plants, as well as renewable sources of supply such as wind and solar systems. At the end of the day the electricity supplied needs to meet the demand, including transmission losses, with a high level of reliability while meeting technical criteria on voltage and frequency. The demand is not fixed but varies, typically on a cyclical basis — daily, weekly, monthly and annually.

Planning for new electricity supply is also complex and may involve different groups. For the purposes of this report it is assumed that such planning is carried out by a single entity, which is referred to as the utility that takes responsibility for ensuring that there is sufficient generating capacity to meet the demand for some specified grid. While the utility may or may plan to purchase power from a range of generators and may own or plan to own some sources of supply, in this report sources of supply are discussed as if they were all part of the one utility.

In general, a utility will seek to establish and maintain a balanced portfolio of generating sources, taking into account a range of considerations that would be expected to include:

— Overall reliability of supply of electricity;
— Demand variations;
— Risk management/minimization;
— Cost minimization;
— Use of domestic resources, including fuels and human resources;
— National/regional policy positions;
— Balance of payments, etc.

When considering the role of nuclear power, in a balanced portfolio it needs to be recognized that constructing a nuclear power plant is a large scale capital project that will be implemented over many years, typically ten years or more, starting with pre-project planning, and one that requires a large front end investment. For a nuclear power plant, amortization of capital costs are the single most important cost factor, and operation and maintenance (O&M) costs, fuel costs, including the cost of uranium, and other costs such as waste management and decommissioning costs are relatively less important but, of course, still need to be considered.

The situation is similar for hydroelectric plants and for some other renewable energy plants, such as wind turbines and solar electricity plants — the major cost is paying back the investment in the facility. For fossil fuel plants, fuel costs are relatively more important or even dominant, and can account for ~40% of total costs for coal or oil fired plants, and up to ~70 % of total costs for gas turbines.

Because of their large capital cost and relatively low operating and fuel costs, nuclear power plants are usually operated more or less continuously to contribute to meeting baseload demand. Of course, they have to be shut down from time to time for refuelling and maintenance, but modern nuclear power plants can operate with an annual load factor of ~85–90 %, averaged over the lifetime of the plant. The corollary is that the economic competitiveness of nuclear power is adversely affected if such plants operate with low load factors. The effect is that plants with relatively lower capital costs and higher fuel costs are more likely to be used for meeting peak demand and so may operate with a much smaller annual load factor, as low as 10–20%, or even less depending on the mix of generating plants available to supply electricity to the grid.

For some generating options, such as hydro or wind, annual load factors may be limited by natural factors. For example, in the case of hydro, load factors may be limited by reservoir capacity and annual variations in water flow — that is, changes in flow during the year. For wind turbines typical annual load factors are ~20–30%, and are rarely greater than 35% because of the natural variability of wind speeds.

Thus, in the INPRO methodology, when comparing the competitive position of nuclear relative to alternative sources of supply, the alternatives need, in general, to be capable of meeting baseload demand and of operating at high load factors. So, nuclear power will most likely be compared with fossil fuelled plants and, in some countries/regions, with hydro.

When considering the acquisition of new generating sources, either to expand the generating system or to replace generating sources as they are retired, system planning will be used to seek an 'optimized' combination of generating options that best takes into account such considerations and the factors mentioned above. Such system planning is not part of the INPRO methodology per se but is considered to be a prerequisite. If such system planning identifies a potential role for nuclear power as a generating source, an assessment in the methodology area of economics can provide useful insights by comparing the competitive positions of nuclear relative to alternative choices using a number of economic indicators. Such an INPRO assessment is not a substitute for system planning but is complementary to it.

Different criteria can be chosen in the economic decision making process when deciding among different options for electricity production. The criteria used will influence the price competitiveness of nuclear energy. For example, in one country the investment decisions could be based on purely commercial rules in a completely deregulated market, whereas in another state a centralized (government) decision making process may be used, leading to different investment figures of merit.

In the first situation, cost of supply may dominate the decision making for a planned energy system in which case the cheapest supply option will be selected, while in the second situation the government may be interested in the deployment of nuclear plants for strategic reasons, in which case higher costs for nuclear power compared with other electricity supply alternatives, up to some level, may be acceptable. An example of such a strategic consideration is the security of energy supply that is one of the energy indicators of sustainable development of a country [4].

Policies that, for example, favour renewable energy sources or recycling, and environmental considerations that, specify emission limits, can influence the choice of technologies to be included in an energy demand/supply planning study. In defining the energy scenario, such political considerations may reflect strictly local policies or, for a regional or global scenario, they may reflect international considerations.

The IAEA offers Member States on request support to perform a national energy system planning study. This support includes the supply of computer tools such as MAED and MESSAGE [4] and corresponding training in the application of these tools.

As mentioned in Section 1.2, a follow-on assessment of economics using the INPRO methodology after the performance of an energy system planning study adds to the transparency of the economic results. The transparency is achieved through the possibility to perform quantitative sensitivity studies on the influence of significant input parameters, e.g. the discount rate, or construction time on key economic figures such as electricity production costs or ROI using the simple methodology NEST (presented in Appendix II). These sensitivity studies can be performed for several types of power plants — nuclear and non-nuclear — in parallel.

The INPRO assessment covers the attractiveness of an investment into nuclear power (in comparison to alternative energy sources) by determining several financial figures of merit such as IRR, ROI and NPV. These figures expand and deepen the understanding of economics since the superiority of an energy supply option depends not only on its power production costs but also on its attractiveness to investors.

Finally, the INPRO methodology addresses the risk associated with the installation of nuclear reactors caused by delays in construction time or by the licensing process.

3. INPUTS NECESSARY FOR AN ECONOMIC ASSESSMENT

This section discusses the inputs necessary for an assessment of a NES in the INPRO methodology area of economics, and provides some background information. In general, most of the necessary economic input data related to the design of a NES can be retrieved from the public domain. However, INPRO recommends that the NESA team establish cooperation with potential suppliers of the NES to facilitate the receipt of reliable input data related to the design.

Within the NESA support package, the assessor is offered a collection of web addresses that contain a significant amount of input data useful for an economic assessment using the INPRO methodology.

Appendix III of this report contains examples of economic parameters — input to and results calculated with NEST — of different nuclear reactors with different fuel cycles, i.e. an LWR with an open fuel cycle or with a partially closed cycle using MOX fuel, and different types of fast reactors with a completely closed cycle.

The report describing the cost estimating guidelines [5] developed by the economic modelling working group (EMWG) within the Generation IV International Forum (GIF) [6] contains, in addition to economic values for some of the reactor designs developed within the GIF project, generic economic data on existing LWRs and associated fuel cycles [7].

3.1. COST DATA FOR DEPLOYING AN NPP

If an NPP is planned to be deployed, an evaluation of its cost competitiveness against alternative energy sources requires financial data on costs and also on revenues — costs for deploying the NPP and for deploying alternative generating sources (AGSs), and revenues to be generated from the sale of electricity produced by these power plants (NPPs and AGSs). As mentioned before (Section 2), AGSs should be power stations suitable for baseload operation as with an NPP.

3.1.1. Concept of levelized unit energy costs

In the INPRO methodology, it is recommended that levelized discounted costs (LDC), also called levelized unit energy costs (LUECs), be used as input for comparing the electricity production costs of different plants. It is a well developed method for many applications and is explained in more detail in Section 4.2 and Appendix I (see also Refs [8, 9]).

The LUEC is equivalent to the average price that would have to be paid by consumers for electricity delivered at the plant bus bar to repay all costs incurred by the owner/operator of a plant such as capital costs, including capital for anticipated backfitting, operating and maintenance costs, decommissioning, and fuels costs at the selected discount rate in a defined time frame (lifetime of the plant).

It is to be noted that a calculation of LUEC is, in principle, not part of an INPRO methodology assessment. However, it is recommended that the assessor determine the value of LUEC using the simple Excel based code NEST for this purpose (see Appendix II) (thereby becoming an analyst).

To calculate the LUEC of a NES — consisting of an NPP and its associated fuel cycle — and of AGSs, the following *economic* input parameters are to be determined:

— *Country specific:* Discount rate, price of unit electricity sold, tax rate (needed only in some options);
— *Power plant specific:* Overnight capital cost, capital investment schedule, contingency cost, owners cost, back fitting cost, decommissioning cost, fixed and variable operation and maintenance (O&M) cost, fuel costs.

If the nuclear fuel costs are calculated directly — considering all stages of a nuclear fuel cycle — the following additional economic input parameters need to be determined:

— *Nuclear fuel cycle specific:* Natural U purchase cost, U conversion cost, U enrichment cost, fuel fabrication cost, and back end cost, such as spent nuclear fuel (SNF) reprocessing cost, storage and disposal cost.

In addition the following *technical* parameters of the NES should be determined:

— *Power plant specific:* Net electric output, lifetime, average load factor, net thermal efficiency.

In case the nuclear fuel costs are calculated directly — considering all stages of a fuel cycle — the following additional *technical* input parameters are to be determined:

— *Nuclear fuel cycle specific:* Reactor first core power density, enrichment of first core and reloads, and losses of uranium (or plutonium) in each stage of the fuel cycle.

These important economic input parameters to calculate the LUEC of a NES and AGS are discussed in more detail in Appendix I.

3.2. ATTRACTIVENESS OF INVESTMENT IN DEPLOYING AN NPP

Investors interested in the deployment of an NPP can look at a variety of financial indicators when evaluating attractiveness of investments, including IRR, the closely related indicator NPV, the payback period, ROI, etc. The financial indicators used in a given market will reflect the investment climate and requirements of a given country or region, including the source(s) of investment funds. It is up to the assessor to determine what financial figures of merit will be used as evaluation parameters for evaluating the attractiveness of an investment in deploying a given NPP. The INPRO methodology recommends that at least the NPV, IRR and ROI be used by the assessor.

As discussed above for LUECs, a calculation of IRR, NPV and ROI is, in principle, not part of an INPRO assessment. However, it is recommended that the assessor determine the value of these parameters using the simple Excel based code NEST for this purpose (see Appendix II) (thereby becoming an analyst).

To calculate the IRR and the ROI using NEST, the reference price per unit of electricity sold (PUES) is required. The assessor should expect to obtain this from the energy scenario under consideration (see Section 2), taking into account historical trends, etc. Knowing the costs for the plant (capital, fuel and O&M costs), the selling price of electricity (PUES), and the average production per year, one can calculate the IRR and ROI.

The estimated IRR from the deployment of the NPP or of the AGS is the discount rate at which the discounted income resulting from the sale of electricity produced by the NPP or AGS, over the lifetime of the plant, exactly balances the discounted costs (capital, fuel, and O&M) of producing the electricity. This is obtained by calculating (see Appendix II) the NPV of the difference between incomes and expenditures using trial discount rates, and adjusting the trial discount rate, in an iterative fashion, to determine the value of the discount rate at which the NPV equals zero. The estimated IRR for the NPP is then compared with the IRR for the AGS to determine if it is superior.

The ROI can be calculated (see Appendix II) from the average net income, i.e. the total income from the sale of electricity produced by the plant over its lifetime less the O&M cost and fuel cost, expressed as a fraction of the capital invested in the plant, over its lifetime, i.e. the capital cost. It should be noted that ROI is not a levelized parameter.

3.3. LIMIT OF INVESTMENT NEEDED FOR DEPLOYING AN NPP

Since the deployment of an NPP, even a so-called small or medium size NPP, requires a significant capital investment, raising the required capital funds in a given market may be a challenge, even if the cost of electricity from the NPP and the investment financial figures of merit are attractive. Thus, the assessor has to evaluate whether the required capital funds can be raised by the future operator (see, for example, Section 6.6 of Refs [9, 10]).

For a private utility as a potential investor, there is usually a limit of investment it can perform based on its total income and profit (in NEST, a simple method is included to calculate such a limit of investment (see Appendix II). If the assessor is from a utility, the assessor would have ready access to this information. In other situations the assessor might need the assistance of a capital market specialist knowledgeable about the capital market in the country or region in which the NPP is to be deployed. Assistance can be obtained from competent organizations such as the IAEA that offer support in using a tool called FINPLAN to determine the impact of an investment into the expansion of an energy system or into a single plant on the financial health of a company.

For a government as investor, the limit is defined by the available budget for a nuclear power programme. The assessor has to determine and assemble the information needed to make this judgment.

The necessary total investment in deploying AGSs such as fossil power plants is usually lower than for an NPP and, therefore, is not considered a limiting factor. However, in case of a hydro plant, the total investment will be comparable.

3.4. RISK OF INVESTMENT IN DEPLOYING AN NPP

To determine the risk of investment, the INPRO methodology has specified logical and numerical criteria related to licensing status of the proposed NPP, NPP project construction and commissioning times, the sensitivity of the costs of electricity and other financial figures of merit to changes in market conditions, and the political climate in the country (or region) in which the NPP is to be deployed.

Information on the licensing status and on project construction and commissioning times should be obtained by the assessor from the supplier of the NPP. Licensing risk is lowest for plants that have already been constructed and licensed for operation in the country of origin or for which the regulator in the assessor’s country has confirmed that the plant could be licensed for operation in that country.

The assessor should have access to the results of a sensitivity study with an appropriate variation of economic input parameters used to calculate the LUEC, IRR, NPV and ROI.

Information on the national political climate regarding nuclear power is needed for an assessment in the INPRO methodology area of infrastructure. The issue of the political climate is included in the area of economics, primarily to ensure that an assessment in the area of infrastructure has been carried out and that the political climate is favourable for deployment of an NPP. If such an assessment has not been done, the assessor in the area of economics should conclude that the investor is faced with an unknown and important risk that needs to be addressed by the proponent of the project. It is not the responsibility of an economic assessor to judge the political climate, but rather to ascertain that the issue has been addressed properly.

The risk caused by licensing, delay of construction and due to a negative political climate is usually considerably lower for alternative generation sources such as fossil power plants than for an NPP, and therefore is not considered as a limiting factor. However, for hydro plants a similar risk is to be taken into account.

3.5. SUMMARY OF INFORMATION NEEDS FOR AN ECONOMIC ASSESSMENT

The discussion presented above has set out various input data that an assessor needs in the area of economics and has also identified sources that could supply such information. This information is summarized in Table 2 and cross-referenced to the discussion above to facilitate its use.

TABLE 2. SUMMARY OF INFORMATION NEEDED FOR AN ECONOMIC ASSESSMENT AND THE SOURCE OF THE INFORMATION

Information needed by assessor	Source of information for a deployment assessment	Discussed in Section
Electricity demand to be met by the NPP or AGS (size of plant)	Energy scenario in country assessed	2
Electricity production cost (LUEC) of the NPP and AG	To be calculated using tools such as NEST, or supplied by technology holder	3.1, 4.2, Appendix I, II
Financial figures of merit (IRR, NPV and ROI) of the NPP and AGS	To be calculated using tools such as NEST, or supplied by technology holder	3.1, 4.3, Appendix I, II
Investment limit of owner/operator of the planned NPP	To be determined by the assessor (e.g. using the NEST code), or supplied by the owner/operator of the plant	3.3, 4.3, Appendix II
Licensing status of the planned NPP	Technology supplier	3.4, 4.4
Project construction and commissioning times of the planned NPP	Technology suppliers	3.4, 4.4
Results of a sensitivity analysis for the planned NPP and AGS regarding LUEC and financial figures of merit	To be performed using NEST.	4.4

The factors involved in developing an NPP are discussed in Section 3.6.

3.6. COST DATA, ATTRACTIVENESS AND RISK OF INVESTMENT IN DEVELOPING AN NPP

The INPRO methodology for the area of economics has been developed primarily for a nuclear technology user to assess the economics of reactors and fuel cycles that the user intends to install, i.e. those that are available in the market as proven designs. However, in principle the INPRO methodology could also be used by a technology developer to assess the economics of a planned development of reactors and associated fuel cycles as discussed in the following.

To assess the *cost competiveness* of a reactor under development against other AGSs, i.e. reactors available in the market, another development option or non-nuclear power stations, the INPRO assessor needs the value of the LUEC of the reactor under development and of the AGS.

To calculate the LUEC of a reactor under development, the same basic input data as for the deployment of a reactor (of proven design) and its fuel cycle are needed, as discussed in the previous sections. They include the overnight capital cost for materials and construction, O&M costs, fuel costs, etc. The costs used in the calculation of LUEC should be representative of the prices to be quoted to a customer, i.e. they should represent the cost to the customer. The price could include a component that represents the payback, to a (private) development organization, of the investment to be made in carrying out the development. The issue of recovering the development costs by follow-up sales of the NPP under development is discussed in Appendix IV, together with a procedure to select an optimal option from several possible options. The value of the LUEC should be provided by the development team to the assessor.

Within the Generation IV International Forum [6], a comprehensive and versatile economic model has been developed for advanced reactors and fuel cycles costs. The Economic Modelling Working Group (EMWG) within GIF has produced detailed guidelines [5] on how to determine (estimate) such costs — including the costs of RD&D — and calculate the LUEC. This GIF cost model is based on a cost of accounts (COA) approach originally developed by the IAEA for the economic evaluation of bids [8]. Taking into account the limited amount of information on costs during the development process of advanced designs, the COA approach developed by the IAEA has been simplified and slightly modified by the EMWG. The cost estimate can be done using a bottom-up or top-down approach depending on the stage of development, i.e. the availability of detailed cost data. EMWG has also developed a corresponding software (Excel sheet) called G4-ECONS [7] that includes all equations presented in the cost estimating guidelines [5]. This economic tool can be used by developers — continuously during the development process with increased accuracy — to calculate the LUEC of advanced reactors, including their fuel cycles[2].

To assess the *attractiveness of an investment* to develop (and deploy) an NPP compared with competing energy sources, the INPRO assessor has to obtain information on the value of financial figures of merit such as IRR, ROI and NPV of the NPP. These data have to be supplied again by the development team of the NPP.

To assess the *risk of investment* the INPRO assessor — when deciding on investing in development — will need information on the results of sensitivity studies for discussion with a marketing team with the aim of determining the sensitivity of financial figures of merit including the LUEC, to changes in market conditions in the countries of prospective customers and, also, to examine the sensitivity of the expected pay back, to a (private) development organization, to changes in these market conditions.

As development proceeds, a marketing team (e.g. as a part of the development organization) will have to perform ongoing evaluations of the political climate in the countries of prospective customers to ensure that the expected customer base has not been eroded, which is clearly a risk of investment in a new design. The political climate has to be made available to the INPRO assessor by the marketing team.

Throughout the development process the development team needs to be aware that, at the time that the NPP is offered for sale, prospective customers will require hard information on the licensing status of the plant, and on project construction and commissioning times to enable them to judge the associated risks.

Thus, licensing activities will need to be initiated at an appropriate stage in the development process and the cost to the developer of these activities will need to be taken into account as an investment cost. The developer should also keep in mind that, in contract negotiations, customers would expect suppliers to agree to penalties to be incurred by the supplier for delayed completion of projects. Thus, the development team needs to determine realistic schedules for construction and commissioning that can form the basis of an appropriate contractual agreement and make them available to the INPRO assessor.

---

[2] NEST and G4-ECONS both calculate the LUEC of a reactor and its fuel cycle in a comparable way. G4-ECONS was developed especially for developers of nuclear technology to compare different options of nuclear designs under development regarding economics. G4-ECONS uses considerably more detailed cost and technical data as input for the calculation of the LUEC compared with NEST.

4. BASIC PRINCIPLE, USER REQUIREMENTS AND CRITERIA OF THE INPRO METHODOLOGY IN THE AREA OF ECONOMICS

The overall goal captured in the INPRO basic principle in the area of economics is to ensure that nuclear power is available and the energy supplied is affordable. The corresponding user requirements are focused on the competitiveness of energy from an NPP in comparison with other energy sources available in the country for the same purpose. The competitiveness of the NPP is checked by evaluating production costs of electricity and financial figures of merit, such as ROI or the IRR. In addition, the potential risks of investment in an NPP are considered.

In some cases, significant differences in the results of economic assessments could be caused by different methods, codes and assumptions used by different assessors. The aim of this section is to provide clear definitions for INPRO methodology economic indicators and acceptance limits so that differences in assessment results are not caused by confusion about terminology and formulas, but can be explained by differences in other factors, such as NES characteristics or market conditions or energy supply options. The section also provides general background information to assist an assessor in understanding the basic principle and user requirements of the INPRO methodology.

In the area of economics, the INPRO methodology has developed a simple structure (see Table 1) of a single basic principle (BP) and four user requirements (UR1 to UR4). For each UR, at least one criterion (CR), consisting of an indicator (IN) and an acceptance limit (AL), is defined.

4.1. INPRO BASIC PRINCIPLE IN THE AREA OF ECONOMICS

As discussed in Ref. [11] the availability of energy is an important indicator of sustainable development in each of its dimensions — economic, social and environmental. Ensuring the availability of commercially supplied energy is one important aspect of governments' ultimate responsibility for national security and economic growth. Not only must energy be available, but it also needs to be affordable. These considerations are reflected in the economic BP, set out below.

INPRO basic principle in the area of economics: Energy and related products and services from nuclear energy systems shall be affordable and available.

The best way of ensuring that nuclear energy and related services are affordable is for the price to the consumer to be competitive with low cost/priced alternatives. If energy and related products and services are to be available, systems to supply the energy and related products need to be developed and deployed. To develop and deploy energy systems requires investment and those making the investment, be they industry or governments, must be convinced that their choice of investment is wise. The alternatives for investment may be other energy technologies seeking investment for development or deployment. So, to be developed and deployed, a NES must compete successfully for investment.

Given the nature of nuclear technology, it is recognized that government policies and actions will have a significant bearing and influence on investor decision making (in some Member States governments may participate in investment), when deciding whether or not to invest in development and also when deciding to invest in technology deployment/acquisition. For private sector investment, profitability and return will be key factors in the business case. For governments, the availability of low cost energy represents an important national asset as it is one prerequisite for a competitive national industry. Other factors include confidence in long term stability and arrangements to protect against political risk.

As mentioned earlier, the INPRO methodology includes four user requirements — UR1 to UR4 — for the INPRO economic BP as laid out in the following sections. All economic URs defined by INPRO are addressed to and have to be fulfilled by the designer (or developer) of a NES.

The role of an INPRO assessor considering whether to deploy a NES, is to check whether the NES offered by the designer is cost competitive, the necessary investment can be raised, and the risk for the investment is tolerable.

The role of an INPRO assessor considering whether to develop a NES is to check whether s it will be cost competitive in the target market, whether the necessary investment can be raised, and whether the risk for the investment will be acceptable. For such an assessor, UR4 in the INPRO methodology has been proposed to check whether the NES under development is sufficiently flexible to be adapted to changing conditions.

4.2. INPRO ECONOMIC USER REQUIREMENT UR1 (COST OF ENERGY)

The definition of UR1 is: The cost of energy supplied by nuclear energy systems, taking all relevant costs and credits into account, $C_{N,}$ must be competitive with that of alternative energy sources, C_A, that are available for a given application in the same time frame and geographical region/jurisdiction.

This UR relates to the cost competitiveness of different energy sources available in a country, region, or globally. In comparing the costs of electricity (or other energy products) from a NES, $C_{N,}$ and competing alternatives, C_A, discounted costs (LUEC) are used, as discussed in Section 3.1. In this comparison all relevant costs are to be included.

Depending on the particular regulations existing in a country, one energy source may be burdened with costs, e.g. for waste management, while another may not. In a number of Member States, the external costs of nuclear power[3] that are not accounted for are small, since producers are required by law to make provisions for the costs of waste management, including disposal, and decommissioning, whereas the external costs of competing (non-nuclear) energy sources that are not accounted for may be significant, e.g. CO_2 emission from fossil power plants. Ideally, all external costs should be considered and, where possible, internalized, when comparing a NES with competing energy systems, but only costs that are internalized (in the price to the consumer) should be taken into account, and other external costs should be ignored.

The single criterion defined for UR1 is set out in Table 3 and discussed below.

TABLE 3. CRITERION FOR UR1

User requirement	Criterion	Indicator (IN) and acceptance limit (AL)
UR1: (Cost of energy): The cost of energy supplied by nuclear energy systems, taking all relevant costs and credits into account, C_N, should be competitive with that of alternative energy sources, $C_{A.}$ that are available for a given application in the same time frame and geographic region/jurisdiction	CR1.1: Cost competitiveness	IN1.1: Cost of energy AL1.1: $C_N \leq k*C_A$ (C_N = cost of nuclear energy, and C_A = cost of energy from alternative source, factor k is usually $\geq$ 1 and is based on strategic considerations)

4.2.1. Indicator IN1.1: Cost of energy

First, the situation of a planned *deployment of a NES* by a technology user will be discussed to be followed by a discussion of a planned *development* of a NES by a technology developer.

Deployment of a NES

The value of indicator IN1.1, i.e. costs of energy (C_N and C_A) of competing energy supply options to be deployed, is determined using a discounted cost (LUEC) model (see Ref. [8] and Appendix II), taking into account all relevant cost determinants for both the NES and the competing energy technology.

[3] By definition, an external cost is a cost imposed on society and the environment that is not accounted for by the producers and consumers of energy.

C_N is, in principle, the LUEC for a complete NES, excluding FOAK cost but including external costs and credits if they are fully included in the price setting mechanism, and using contingency allowances and a discount rate that reflects the economic decision making investment environment. In practice, a technology user would compare the cost of electricity from the NPP, which would include an allowance for the back end costs for waste management and decommissioning for the NPP, with that of the alternative energy source. Costs of other components of the NES, including costs for decommissioning and managing wastes from these components, would be reflected in the cost of fuel.

C_A is the LUEC for the (strongest) competitor A (for power generation investment), excluding FOAK cost but including external costs and credits if they are fully included in the price setting mechanism, and using contingency allowances and the same discount rate[4] as applied for calculating C_N . Further, the competing alternative energy source is to be available for the same application in the same time frame and geographic region/jurisdiction. This is an important limitation since, as discussed in Section 2 (energy system planning), an NPP is usually operated at high load factors, primarily for meeting base load demand. So, usually, the competing alternative will be a fossil fuelled plant, e.g. coal, oil or a combined cycle gas turbine plant or, in some jurisdictions, a hydro plant. Further, the cost comparison should be based on costs for the relevant region/market and the time frame for the deployment of the NES.

The concept of LUEC

The basic concept of LUEC is based on expressing all costs and revenues that occur at different times in their equivalent value at a single point in time, for example the start of commercial plant operation, time t = 0, using a discount rate, r, that represents that time value of money. Since the start of construction, and therefore expenditures, begin several years before the plant starts operation, the value of the investment made from the start of the construction until the start of plant operation is greater than the so-called overnight construction cost, — the money spent in a given year prior to plant operation is increased by a factor $(1 + r)^{-t}$, where t is the time of the expenditure prior to plant startup. Note that since t is the time prior to the start of construction, t is a negative number so that the factor and $(1 + r)^{-t}$ is greater than 1. So, to calculate the investment cost levelized to time 0, one needs to know the time for construction and the cash flow to come up with an accrued cost for construction. Various other project costs that are assigned to the project, including project management costs, site preparation costs, and others also need to be accrued (see Appendix I).

Once the plant is commissioned and enters into commercial operation, assumed to be at time 0, the investment is complete. Then revenues begin to flow, since it is assumed that the electricity is sold at some price, P. The net revenue earned in year t after the start of plant operations is discounted to year 0, by a factor $(1 + r)^{-t}$. Since t is the time after the start of plant operation, t is a positive number and hence the factor $(1 + r)^{-t}$, is less than 1. The *net revenue* in a given year is the *difference between gross annual revenue* and the *annual costs in that year* for fuel, for operating and maintenance expenditures, for annual fees charged for waste management and decommissioning and for any other costs. The *gross annual revenue* in year t is the output of the plant in MW(e), times the price per kW·h, times 1000, times the number of hours in one year, times the load factor in that year — normally assumed to be the average load factor over the plant's lifetime.

The discounted net revenues are then summed over the plant lifetime used in the analysis, to arrive at the total discounted net revenue. The LUEC is therefore equal to the price, P, such that the total discounted net revenue just equals the accrued costs for construction, including all associated project costs.

Another way of expressing LUEC is to say that it is the price at which electricity would be sold such that the net present value of all the flows — cash out and cash in — from the start of the project to the end of plant life (assumed for the calculation) is equal to 0.

LUEC is a useful tool for comparing costs of different types of generating options with different cost components and is widely used for this purpose. On the other hand its value should not be overemphasized. It tells one part of the economic story but not the complete story. For example, at higher discount rates, revenues encountered after 20 years of plant operation have a very small, almost negligible, value even though the plant

[4] In some studies, different discounts rates are used for C_N and for C_A, to reflect a higher risk for one option compared with the other. The difference could also be caused by finance arrangements (debt/equity), government incentives, or other factors. Usually the nuclear risk is considered to be higher. In the INPRO methodology, the same discount rate should be used for C_N and C_A because risk is considered separately (see Section 4.4, UR3).

can be expected to generate power and hence, income, for a further 30–40 years or more. This added value is not reflected in the comparison of LUEC.

Also, it is possible to use different modelling approaches to estimating LUEC values. For example, one approach is to express all cost and revenues in constant money (e.g. US dollars) without inflation. Another approach is to take inflation into account using so-called current money (see also Appendix I). Deciding whether or not to include inflation will affect the discount rate used in the calculation. One can also include changes in estimated real costs as a function of time or use values that are time independent.

The NEST code that has been developed as an INPRO support tool offers the user a number of options, for calculating LUEC. This code is described in Appendix II. When using the NEST code, it is recommended to use the simplest approach, which is based on the model presented in Ref. [12]. Then, as experience is gained, a more complex model can be used, for instance if it better represents the way such calculations are performed in a given Member State or market, or is more suited to a given study.

In selecting a non-nuclear alternative for comparison, the *strongest competitor* has to be chosen for calculating C_A. Competitiveness, however, is an inherent 'moving target' [13], and so, with time the strongest competitor could change from one energy option to another. In addition, future price changes and uncertainties should be considered, e.g. is a given fuel price expected to increase or decrease with time.

Development of a reactor and its fuel cycle

In this case, C_N is the LUEC for a reactor and its fuel cycle to be developed (or being developed) and C_A is the LUEC for a competitor A to the design to be developed. Such a competitor could be a reactor and its associated fuel cycle licensed and in operation with the same developer or from a competing institution.

At the time when evaluating whether to make or continue an investment in developing a nuclear reactor and its fuel cycle, the cost estimate C_N (for the product of the reactor, i.e. electricity) should include a component to recover the development costs with a suitable return (see Appendix IV). In assessing case for development, generating costs would usually be based on the costs for repeat reactor units or Nth of a kind (NOAK), rather than for an FOAK unit. Many of these costs, particularly at early stages of development, may have uncertain values, and hence may encompass or require ranges of estimates.

Thus for development of a reactor, a sensitivity analysis should be used in assessing the impact of potential variability in costs (see Section 4.4.3). Such a sensitivity analysis can be used to identify the relative importance of the various cost determinants and also to identify opportunities for cost reduction. The completeness and the ranges of the cost determinants may be regarded as a measure of the maturity of the new design. As the new design proceeds through the stages of development (conceptual, feasibility, prototype, FOAK) the cost estimates will be refined and the uncertainties reduced. But costing a new design as it evolves is an important and necessary discipline to ensure that, once developed, it will be cost competitive.

In the *near to intermediate term* (over the next 20–50 years) in many Member States, fossil fuelled thermal plants, e.g. coal fired or combined cycle gas turbines, are likely to be the prime competition with nuclear for electricity production . Thus, reductions in the specific capital costs of nuclear power plants while maintaining low fuel and O&M costs, as well as low waste management and decommissioning costs, would improve the competitive position of nuclear power.

In the *longer term* (the next 50–100 years), renewable energy sources such as photovoltaic and wind power may represent the primary competition for nuclear energy based on costs. These technologies are characterized by low, if not zero, fuel costs and, if successfully developed, low maintenance costs. The main cost is the capital cost of construction and installation, including the capital cost for needed backup storage and/or alternate sources of energy and the 'cost' of land use. The need for backup power is based on their inherent nature, i.e. renewable energy sources such as wind and solar do not generate power continuously. So, as they gain market share, it becomes increasingly important to provide backup sources and the cost of doing so must be taken into account. The higher load factors expected from nuclear plants compared with those from renewables represents a competitive advantage for nuclear. In recent years average availability factors >90 % have been achieved. With nuclear reactors under development, even higher availability factors of ~95 % should be achievable.

If the total unit energy cost of nuclear energy is to be competitive, the cost of the fuel used in the energy production machine — the reactor — must remain acceptably low. The operator of a nuclear energy plant will act as a customer for the products from fuel cycle facilities and new fuel cycles must be competitive with alternative fuel strategies, which may be coupled with alternative reactor designs. Thus, the capital cost and the O&M costs of the nuclear fuel cycle facilities other than the reactor must be sufficiently small that the fuel costs to the reactor operator are competitive. Fuel cycle facilities also produce waste, which must be safely managed, including placing it in a safe end state and, in due course, the facilities have to be decommissioned. The cost of all these activities and the associated waste management facilities must be such that the fuel costs remain competitive.

Overall, it is clear that, for NES, the capital costs, the O&M costs, the fuel costs, the waste management costs, and the decommissioning costs must individually and collectively be sufficiently low to make the total unit cost of the energy product competitive. Thus, from an economic perspective, the developers of a NES need to work to decrease overnight construction costs, decrease construction times and hence interest during construction, decrease O&M costs, increase life cycle average availability, and extend plant lifetimes, all without compromising safety or environmental performance.

4.2.2. Acceptance limit AL1.1

AL1.1 is defined as: $C_N \leq k*C_A$. This means that the discounted energy cost (LUEC) of a NES to be deployed or developed should be comparable, within a factor of k, to the LUEC of an available system with a competing energy source. As mentioned above, the LUEC of a NES and of a given competing energy source can be calculated using NEST (see Appendix II). Again, the case of deployment and development are distinguished. First, the case of deployment will be considered.

Deployment of a NES

In the case of *deployment* of an NPP, the competing energy sources are alternative (non-nuclear) energy sources available and suitable for base load in the country assessed, e.g. fossil power plants or hydro plants.

The factor k used in comparing C_N to C_A could, in principle, be 1, less than 1 or greater than 1 in a given Member State or region, depending on whether or not nuclear costs are offset by other considerations relative to the alternative energy source or vice versa. Thus, Member States and investors should determine the value of k depending on their particular circumstances. Such a determination could well be made in the decision making process as part of taking into account factors for which it is hard to assign definitive costs, such as the cost of externalities. It was already mentioned above that LUEC does not present a complete economic picture and in that discussion the impact of high discount rates devaluing the worth of power generated later in the life of a plant was discussed.

In a given country or region in addition to economics many other factors can enter into the decision making regarding the choice(s) of energy supply (as discussed in Section 2, energy system planning and the role of nuclear power). These include, for example: considerations of security of energy supply, long term stability in energy costs, diversity of energy supply technologies, i.e. the energy mix, of both the market as a whole and of a given producer/supplier; the desire for industrial development and the role nuclear technology can play in such development; judgments about environmental impacts, either positive or negative, avoided emissions, safety, sustainability, waste management; utilization of domestic resources, such as mineral and labour resources and industrial capacity; public and hence political acceptance, etc. In some jurisdictions, land use can be an important factor. The much higher energy output of nuclear plants for a given plant footprint, MW(e)/hectare, may then be one of nuclear technology's competitive advantages compared with other sources such as renewables (see, for example, Ref. [14]).

Such considerations may lead decision makers and investors, particularly governments, to accept a somewhat higher cost for one energy option compared with an alternative, i.e. select a value of k greater than 1. See, for example Refs [15, 16], which discuss the credit that could be assigned to the security of energy supply in Japan.

As mentioned in Section 2, system energy planning can be used to seek an optimal combination of generating options. In such planning, a variety of constraints and drivers can be included to reflect some or all of the issues discussed in the preceding paragraph. As well, policies established by state or national governments may have an important impact on choices. So, if energy planning has determined that there is a defined role for nuclear power within the optimized mix of generating options the comparison of C_N to C_A, is not, of itself a determining consideration. But if C_N is larger than C_A, the comparison will show this explicitly and the assessor might set out the benefits and explanation of why the cost difference is acceptable in the circumstances.

Once a new NPP has entered into service, it is important that actual costs of generation be determined so that future energy planning studies take experience with recent projects into account. If the actual costs of nuclear exceed those used in planning, the results of a new energy planning study, which factors in actual performance, may well lead to a different mix of generating sources. If the actual C_N is consistently less than the actual C_A, there would be a preference for a larger role of nuclear in the mix and vice versa.

In the case where C_N is larger than C_A, C_N might be compared with the current selling price of electricity to determine whether the introduction of a first or additional nuclear plant will put upward pressure on the price of electricity. If that were the case, communicating the need for and desirability of the chosen optimized mix of sources will become important in gaining/maintaining public support (see also Volume 3 of the INPRO Manual discussing public acceptance).

Development of a nuclear reactor and its fuel cycle

In the case of a planned (or ongoing) development of a NES (or a facility thereof) the competing energy source could be a comparable NES (or a facility thereof) licensed and already in operation. Examples of such a comparison can be found in Ref. [17]. Similar to deployment, in the case of development the factor k could be 1 or greater than 1 (see also Appendix IV for a discussion of economics and the development cycle). A factor k greater than 1 could be justified by advantages of the design under development in other areas of the INPRO methodology, such as availability of resources (Volume 8 of the updated INPRO Manual) or proliferation resistance (Volume 5 of the updated INPRO Manual).

Member States may well develop their own specific criteria for some of the INPRO user requirements, taking their national boundary conditions and circumstances into account.

4.3. ECONOMIC USER REQUIREMENT UR2 (ABILITY TO FINANCE)

The definition of UR2 is: The total investment required to design, construct and commission nuclear energy systems, including interest during construction, should be such that the necessary investment funds can be raised.

There are two aspects to investment, somewhat related to each another, namely, the attractiveness of the investment in terms of the financial return to be expected and the size of the investment that is required. Even if the financial indicators used to analyse return are attractive, a given utility may not have the wherewithal to raise the funds needed — neither from its own resources nor from other investors.

The total investment required to deploy a given NES, or component thereof, comprises the costs to adapt a given design to a given site, and then to construct and commission the plant, including the interest during construction. The latter depends on construction time and the time to commission. A universally applicable criterion for what constitutes an acceptable ‘size’ of investment cannot be defined a priori since this will vary with time and region and will depend on many factors, such as alternatives available, etc. But a judgment must be made that the funds required to implement a project can be raised within a given expected investment climate. Factors influencing this ability may include the overall state of the economy of a given region/country, the size of the investment relative to a utility’s annual cash flow (and hence the size of the unit relative to the size of the grid), and the size of the investment compared with that needed for alternative sources of supply.

The attractiveness of an investment may be expected to have some influence on the acceptability of the size of the investment but in the INPRO methodology the two are treated as independent. Since, however, there is some influence of attractiveness on acceptability of size, we treat attractiveness first.

The attractiveness of an investment is usually quantified by determining economic parameters called financial figures of merit. Examples of such figures are IRR, the ROI, NPV of cash flows, and payback period. IRR and NPV are more or less two sides of the same coin, as are ROI and payback time.

INPRO has defined two criteria for UR2, one related to the attractiveness of the investment and the other to the size of the investment (Table 4).

TABLE 4. CRITERIA FOR UR2

User requirement	Criterion	Indicator (IN) and acceptance limit (AL)
UR2: (Ability to finance): The total investment required to design, construct, and commission nuclear energy systems, including interest during construction, should be such that the necessary investment funds can be raised	CR2.1: Attractiveness of investment	IN2.1: Financial figures of merit AL2.1: Figures of merit for investing in a NES are comparable with or better than those for competing energy technologies
	CR2.2: Investment limit	IN2.2: Total investment AL2.2: The total investment required should be compatible with the ability to raise capital in a given market climate

4.3.1. Criterion CR2.1: Attractiveness of investment

Indicator IN2.1: Financial figures of merit.
Acceptance limit AL2.1: Figures of merit for investing in a NES are comparable with or better than those for competing energy technologies.

Investors can look at a variety of financial indicators when evaluating investments. The financial indicators used in a given region will reflect the investment climate and requirements of a given country or region, including the source(s) of investment funds. In some countries or regions implementation of a NES will require private sector investment, e.g. in deregulated electricity markets, while in other countries or regions installment of a NES may require government investment or guarantees, e.g. in countries embarking on a nuclear power programme.

Private sector investors will be attracted by a competitive IRR, provided the IRR is commensurate with their judgment of associated risks. However, the NPV of cash flows may be more suitable for government investors than private sector investors because this financial figure may facilitate taking into account other benefits such as security of energy supply and technology development. The ROI may be attractive as an indicator that is complementary to the IRR.

In the end, the acceptance limit is that the values of the financial indicators chosen, for a given NES, be attractive compared with investments in competing energy technologies. To be attractive, the values for the NES must be at least comparable to values for competitive energy sources and preferably better.

For indicator IN2.1, three items of financial figures of merit, namely, IRR, ROI and the NPV of cash flows are recommended as *evaluation parameters* (EP2.1.1 to EP2.1.3), with corresponding acceptance limits, as discussed below.

IRR, ROI and NPV can be calculated using NEST, described in Appendix II.

4.3.1.1. Evaluation parameter EP2.1.1: Internal rate of return

Evaluation parameter EP2.1.1 is defined as the *internal rate of return* at the calculated real selling price of electricity produced by a complete NES (IRR_N). A more precise definition is: The IRR produced by selling the net electricity produced by a NES at the defined real reference price per unit of electricity sold (PUES), excluding (external) costs not defined in price setting mechanisms and including costs for expected life cycle operation, decommissioning and waste management.

The IRR depends on factors such as the PUES, the load factor of the plant, and the costs (LUEC) of production including amortization cost, O&M costs, fuel costs, waste management costs, etc. The IRR is obtained by calculating the NPV of the difference between incomes and expenditures. In this calculation trial discount rates are used, and adjusted in an iterative fashion to determine the value of the discount rate at which the NPV equals 0, which is the value of IRR.

For consistency, the IRR needs to be calculated using a similar modelling process as chosen for calculating LUEC. So, if inflation is not included in calculating LUEC, it would not be included in calculating IRR. In this case, the IRR would be less than what would arise from a model that included inflation.

The IRR would normally be calculated for the total cash flow of a single NPP. As for LUEC, the economics of fuel cycle facilities is covered within the fuel costs of the NPP. So, if it is foreseen that the price of uranium is expected to increase over the life of the NPP, such a price increase should be reflected in the fuel cost used in the analysis. Only costs and credits that are defined in the price setting mechanism (see Appendix I) should be considered. Externalities should be excluded if they are not supported by an acknowledged price calculation process.

4.3.1.2. Acceptance limit AL2.1.1

The acceptance limit AL2.1.1 for evaluation parameter EP2.1.1 reads as follows.

Acceptance limit AL2.1.1: $IRR_N \geq IRR_A$

The internal rate of return IRR_N of an investment into a NES should be comparable, i.e. higher or at least equal than IRR_A an investment in competing (alternative) energy technologies.

In case of an investment into a planned deployment of an NPP the competing technology could be either another type of NPP or most probably a non-nuclear generating technology available and suitable for base load in the country assessed.

In case of an investment into a planned development of an NFC facility/component of a NES, the competing technology would be a licensed and operating facility of an existing NES.

As was discussed above, when comparing the LUEC of competing energy supply options, if energy planning has determined that there is a defined role for nuclear power within an optimized mix of generating options the comparison of IRR_N to $IRR_{A,}$ is not, of itself a determining consideration. But if IRR_N is less than IRR_A, the comparison will show this explicitly and the assessor might set out the benefits and explanations of why the difference is acceptable to the investor in the circumstances.

4.3.1.3. Evaluation parameter EP2.1.2: ROI

Evaluation parameter EP2.1.2 is defined as: The life cycle plant average ROI of a complete NES (ROI_N). It can be even more precisely defined: The ROI calculated for the average life cycle total plant invested capital and life cycle average operating net income produced from the sale of electricity.

The return on investment, ROI, of an investment into a NES — also like IRR — depends on the price of electricity, the load factor and production costs. The ROI is calculated from the average net annual income, i.e. the total income from the sale of the output (electricity or heat) produced by the plant over its lifetime less O&M and fuel costs and other costs such as waste management and decommissioning costs over its lifetime, expressed as a fraction of the capital invested in the NES.

Due to the simplicity of ROI, even for a complex NES with several plants of different type, a single ROI for a NES consisting of several plants to be deployed could be calculated using the average net income and investment per plant. On the other hand, for a technology user evaluating the use of nuclear power as an option, the INPRO methodology recommends that the ROI be calculated for a single NPP. So, in this case, the ROI is the ratio of the net annual income to the capital investment averaged over the lifetime of the plant. In addition, only the investment in the generating plant is included and the investment in the necessary fuel cycle facilities is not explicitly included; however, that investment would be reflected in the fuel costs used to calculate net income, and thus is ultimately accounted for.

ROI is not a levelized parameter. Thus, it is not sensitive to discount rate as is the case for LUEC. So, in the case where a high discount rate is used in calculating LUEC, the income from the production of electricity over the lifetime of the plant contributes to the ROI. In this way, the evaluation of ROI complements the evaluation of LUEC to present a more comprehensive economic picture.

Life cycle plant investment means that all the investments, including back fitting and major refurbishments, are taken into account, if it is foreseen that such investments are needed during the operating lifetime of the plant, and they may be accounted for by an annual charge and become in effect an annual operating cost. If this is done, then the ROI would be based on annual net income and the initial capital investment. Under these circumstances, INPRO would recommend that IDC be included in calculating the ROI when considering a single NPP. If, however, investments in foreseen costs are considered explicitly, as a capital investment, INPRO would recommend not including IDC.

Life cycle average operating income covers the situation that there could be some fluctuations in the operating income during lifetime, e.g. due to a low load factor during a back fitting period, or during the first operating years.

4.3.1.4. Acceptance limit AL2.1.2: Limiting ROI

The acceptance limit AL2.1.2 for evaluation parameter EP2.1.2 is as follows:

Acceptance limit AL2.1.2: $ROI_N \geq ROI_A$

This means that ROI for a planned NES (ROI_N) should be comparable with the return of investment in a competing energy technology (ROI_A).

In case of an investment into a planned *construction of an NPP*, the competing technology would be a non-nuclear generating technology available and suitable for base load in the country being assessed.

In case of an investment into a planned *development of another NFC facility* of a NES, the competing technology would be a licensed and operating NFC facility of an existing NES.

As was discussed above, if energy planning has determined that there is a defined role for nuclear power within an optimized mix of generating options the comparison of ROI_N to $ROI_{A,}$ is not, of itself a determining consideration. But if ROI_N is less than ROI_A, the comparison will show this explicitly and the assessor might set out the benefits and explanation of why the difference is acceptable in the circumstances. In any case, actual performance needs to be tracked and be taken into account in ongoing energy optimization planning studies.

4.3.1.5. Evaluation parameter EP2.1.3: NPV

NPV analysis is a useful tool for looking at project cash flows and the recovery of investments. In principle, one can use actual investments and incomes, expressed in the actual values. Such an analysis would not account for the time values of money and so in INPRO methodology discounted values are used, namely the NPVs of the cash flows. So, for a given project investment, the cash flow starts out as a negative value at the start of a project, and the cash flows and their integrated values, the NPV of the total cash flow, continues to be negative as cash flows out during construction. Once construction ends and cash starts to flow in from the sale of energy (electricity), annual cash flows turn positive, as does the slope of the NPV. With a positive slope from net revenues the NPV increases over time, rising towards zero, and then turning positive. The NPV will then continue to increase until the end of plant life, at which point it would be expected to decrease as money is spent on plant shutdown and decommissioning. Overall, the NPV should remain positive once decommissioning is complete if the project is to return a net benefit to the investor; the greater the NPV the greater the net benefit. In INPRO methodology, NPV can be used as an evaluation parameter for measuring the net financial benefit of a project investment. In principle, such a parameter can be used for looking at a complex mix of projects involving a variety of project investments and revenues. In practice, however, it is recommended to limit the time horizon for estimating NPV to a few decades — no more than four and preferably three or less.

Evaluation parameter EP2.1.3 is defined as the NPV at the calculated real selling price of electricity produced by a complete NES (NPV_N). A more precise definition is: the NPV produced by selling the net electricity produced by a NES at the defined real reference PUES, excluding (external) costs not defined in price setting mechanisms and including costs for expected life cycle operation, decommissioning and waste management.

The NPV depends on factors such as the total plant investment, the PUES, the load factor of the plant, and the costs of production including, O&M costs, fuel costs, waste management costs, etc. NPV is obtained by calculating the NPV of the difference between incomes and expenditures, discounted to a reference point in time.

The NPV would normally be calculated (using NEST, see Appendix II) for the total cash flow of a single NPP. In this case, the NPV would be calculated using a similar modelling process as chosen for calculating the LUEC for the NPP (Recall that LUEC is the price that results in an NPV of 0.). So the reference time for discounting purposes would be the start of plant electricity generation, and if inflation were not included in calculating LUEC, it would not be included in calculating NPV. In this case, the NPV would be less than what would arise from a model that included inflation.

Since the NPV is based on the actual selling price of electricity, which would be expected to be higher than the LUEC, the NPV would be expected to be a positive number. Since it represents the total net value of the investment, discounted to time 0, its absolute value will depend on the size of the investment. For this reason INPRO recommends that the NPV be normalized to the initial (discounted) capital investment made up to the start of plant operation or to the power output of the plant. As for LUEC, the economics of fuel cycle facilities is covered within the fuel costs of the NPP. So, for example, if it is foreseen that the price of uranium is expected to increase over the life of the NPP, such a price increase should be reflected in the fuel cost used in the analysis.

4.3.1.6. Acceptance limit AL2.1.3: Net present value

The acceptance limit AL2.1.3 for evaluation parameter EP2.1.3 reads as follows:

Acceptance limit AL2.1.1: $NPV_N > NPV_A$

The (normalized) NPV_N of an investment in a NES should be comparable, ideally greater, than the NPV_A for an investment in competing energy technologies.

In the case of an investment in a planned NPP, the competing technology would be a non-nuclear generating technology available and suitable for base load in the country being assessed.

In the case of an investment into a planned development of an NFC facility/component of a NES, the competing technology would be a licensed and operating facility of an existing NES.

As has been discussed several times, if energy planning has determined that there is a defined role for nuclear power within an optimized mix of generating options, the comparison of NPV_N to NPV_A is not of itself a determining consideration. But if the NPV_N is less than NPV_A, the comparison will show this explicitly and the assessor might set out the benefits and explanations of why the difference is acceptable to the investor in the circumstances. In any case, the actual performance needs to be tracked and be taken into account in ongoing energy optimization planning studies.

4.3.1.7. Final assessment of acceptance limit AL2.1

Acceptance limit AL2.1: Figures of merit for investing in a NES are comparable with or better than those for competing energy technologies.

The acceptance limit AL2.1 of CR2.1 is met if the financial figures of merit selected by the assessor meet their corresponding limit.

4.3.2. Criterion CR2.2: Affordability of investment

Indicator IN2.2 is defined as: The highest single plant total investment up to commissioning the reactor within a complete NES.

Acceptance limit AL2.2: The total investment required should be compatible with the ability to raise capital in a given market climate.

4.3.2.1. Indicator IN2.2: Total investment

The total investment consists of the overnight capital, the interest during construction (the size of which depends on construction and commissioning times), contingency allowances, owners cost and (if not considered in the O&M cost) the capital needed for (foreseen) back fitting and decommissioning. It can be calculated using NEST (see Appendix II).

This indicator has been formulated in a general sense to cover investments in the different facilities of a NES, such as one or more NPPs, fuel cycle facilities and waste management facilities. For simplicity, it is recommended that an initial assessment focus on the investment needed for an NPP, since this is the energy machine and has to be made if a given country is to benefit from the energy produced by nuclear power. Of course, in a given country, there may be interest in investing in front end fuel cycle facilities, such as mines or fuel manufacturing facilities, but in general the investment in an NPP is more challenging. And, if this investment is made and nuclear power becomes/continues as part of a balanced portfolio of generating plants, the revenue from the NPPs can be used to finance the associated waste management activities and facilities. And investments in front end facilities can be evaluated taking into account the status of nuclear power in the country and worldwide. Consequently, in the discussion below only the issue of investing in the NPP is considered.

FOAK costs, together with R&D costs, would in general not be explicitly included in this indicator because such costs are different from simple electricity oriented fundraising mechanisms and are more related to R&D investment policies used by governments and/or private investors. FOAK and R&D costs born by the developer would be expected to be reflected in prices quoted by a vendor/developer, and so such costs would be implicitly included.

But should a company (utility) consider the purchase of an FOAK reactor, requiring significant FOAK investment by the purchaser, the company would have to take this investment into account in one way or another. It might simply accept the cost and include it in its analyses. But, generally, such a company would be expected to negotiate for some additional benefit. For example, it could negotiate with the supplier to secure price reductions for future orders, or even to share in the profit from future sales of the reactor to other utilities. In such cases, FOAK investment might be analysed using different variables/parameters. Nonetheless, the total investment required for the project would need to be raised and so in this circumstance the additional FOAK investment would need to be included.

4.3.2.2. Acceptance limit AL2.2: Investment limit

Acceptance limit AL2.2: $\text{Investment}_{\text{N}} \leq \text{Investment}_{\text{LIMIT}}$

$Investment_{LIMIT}$ is the maximum level of capital that could be raised by a potential investor in the market climate. To meet this limit the investment needed for installing an NPP $investment_N$ must be equal or lower than the maximum capital that can be raised by a potential investor.

The limit is strongly dependent on the investment environment in which an NPP is to be deployed, above all on the nature of the organization making the investment — a private sector commercial enterprise operating in a deregulated market, a private sector enterprise operating in a regulated market, or a State owned company.

In case a private company (utility) is planning to install an NPP, the maximum investment it can raise for this purpose (making a sound business case) will depend on the total size of the national electricity market, the utility's share of the total market, and its profit margin. A simplified example how to determine the maximum reasonable investment of a private investor is available in NEST (see Appendix II).

The source of funds — whether the utility obtains funds from external investors (see Refs [9, 10]), or are drawn from the utility's own capital reserves (equity) or some combination of the two sources will influence this limit (see also Appendix I, source of capital). For example, if only reserves are used the size of the reserves will establish an upper limit, taking into account that the utility would probably not want to draw down all its reserves. If external investors are involved they would want to be assured that the utility's cash flows will be sufficient to pay back the investment while also covering all other costs to which that the utility is exposed, including total operating and maintenance costs, payback of earlier investments etc.

As noted in Section 3.3, the IAEA offers support to Member States on how to determine the economic viability of investing in an expansion of an energy system or in a single power plant. The Excel based tool to be offered is called FINPLAN [4], which helps to analyse the impact of a planned investment on the financial health of a utility planning to invest.

In case a government is planning to install a NES, the investment limit could be defined by the budget available for the national nuclear power programme. A variety of additional factors could influence the available budget, including the following:

— A State oriented approach might establish a limit for any given project at some fraction of the total investment budget to be used in the energy sector.
— The limit could be influenced by issues related to the currencies that are required for debt servicing.

In effect, the acceptance limit for deployment of the first few NPPs in a country is that the total investment required should be compatible with the ability to raise the necessary capital in the country at the time of committing to construction of the NPP. And for the deployment of additional units of the same basic type of NPP, the acceptance limit is that the total investment required is compatible with the ability to raise the necessary capital in the country at the time of committing to construction of the additional units, taking into account actual performance and costs for nuclear power in the country.

In case of an investment into a planned (or ongoing) development of a NES (or component thereof), the investment limit could be defined by the available budget of the organization involved.

4.4. ECONOMIC USER REQUIREMENT UR3 (RISK OF INVESTMENT)

User requirement UR3 states: The risk of investment in nuclear energy systems should be acceptable to investors.

As for any large scale project, there are many risks that can impinge on an NPP project. These include, among others:

— Technology risk: Is the design mature, so that there is confidence that the plant performance will not be adversely affected by unforeseen technical problems and so will operate at the planned lifetime capacity?
— Schedule risk: Will the NPP be constructed and brought into service on the schedule used in financial analyses?
— Licensing/regulatory risk: Will there be regulatory issues that impinge on the construction schedule and operating capacity of the plant?

INPRO has defined several criteria for UR3 (Table 5).

TABLE 5. CRITERIA FOR UR3

User requirement	Criterion	Indicator (IN) and acceptance limit (AL)
UR3 (Investment risk): The risk of investment in nuclear energy systems should be acceptable to investors	CR3.1: Maturity of design	IN3.1: Technical and regulatory status AL3.1: Maturity of technical development and status of licensing of a design to be installed or developed
	CR3.2: Construction schedule	IN3.2: Project construction and commissioning times used in economic evaluation AL3.2: Times for construction and commissioning used in economic evaluation are sufficiently accurate, i.e. realistic and not optimistic
	CR3.3: Uncertainty of economic input parameters	IN3.3: A sensitivity analysis of important input parameters for calculating costs and financial figures of merit has been performed AL3.3: Sensitivity to changes in selected parameters is acceptable to investor
	CR3.4: Political environment	IN3.4: Long term commitment to nuclear option AL3.4: Commitment sufficient to enable a ROI

4.4.1. Criterion CR3.1: Maturity of design

Indicator IN3.1: Technical and regulatory status.

Acceptance limit AL3.1: Technical development and status of licensing of a design to be installed or developed are sufficiently mature.

4.4.1.1. Indicator IN3.1: Technical and regulatory status.

Regulatory and technical uncertainties represent a project cost and schedule risk and a risk that the plant will not operate with the load factor assumed in the financial analysis. Regulatory uncertainties are linked to technical maturity, and so in the INPRO methodology the two are considered together. Broadly speaking, two different situations can be identified — deciding whether to invest in technology development and deciding whether to invest in technology deployment.

When investing in technology deployment, there is a requirement that the technology's maturity and safety have been adequately demonstrated in the development programme and licensing process as part of the technology adoption process.

In the case of technology development, a judgement is required that once development is complete the technology can be licensed in the country of origin. Thus, early in the development process, and before significant investment has been made, there is a requirement that the development team start a dialogue with the regulator to identify issues of concern and to establish a process and plan for addressing these issues during development so that sufficient information would be available to license an FOAK plant.

4.4.1.2. Acceptance limit AL3.1: Technical development and status of licensing

As shown below, AL3.1 of CR3.1 is split into four different parts depending on the situation, i.e. it is adapted to the situation in a country planning to install its first NPP, add a new NPP to an existing NES, and install an FOAK (AL3.1.1, AL3.1.2 and AL3.1.3, respectively), and for the case that a technology developer is planning to develop a NES (AL3.1.4).

Acceptance limit AL3.1.1: For deployment of the first few NPPs in a country. Plants of the same basic design have been constructed and operated.

Acceptance limit AL3.1.2: For deployment of additional units of the same basic type of NPP. Plants of the same basic design have been licensed, constructed and operated in the country and there are no outstanding technical or licensing issues which impact negatively on plant performance.

Acceptance limit AL3.1.3: For deployment of an FOAK plant in a country with experience operating NPPs. Design is licensable in the country of origin.

The acceptance limits AL3.1.1 (first NPP), AL3.1.2 (follow-up units) and AL3.1.3 (FOAK) are discussed together below.

In the case of technology deployment, regulatory risk is minimized if the plant under consideration is similar to a plant that has already been licensed and operated, preferably in the country in which the plant is to be deployed. For a country deciding whether to deploy its first NPP, this is not possible. Then, the regulatory risk is minimized if plants of the same design have been licensed and operated in the country of origin. Thus, a country adopting its first nuclear power plant would generally want a plant that is similar to plants already operating in the country of origin, i.e. proven technology.

In the case of an innovative design (an advanced design which incorporates radical conceptual changes in comparison with existing practice), construction and operation of a prototype or an FOAK plant will provide confidence that technical uncertainties affecting safety have been addressed and lay the foundation for the licensing of additional plants, in the country of origin and also for deployment outside the country of origin. Thus, for a country adopting its first NPP, the minimum requirement is that similar plants have been licensed and operated. These arguments also apply to a country that has experience with operating NPPs but is considering a new type of plant.

Once a utility has had experience with a given type of plant and is considering the deployment of additional units of the same basic type, an assessor should still determine whether or not there are outstanding technical or regulatory issues that might impact negatively on project performance (retrofits, schedule delays, etc.) and/or plant operational performance. If there are such issues they should be taken into account in the project schedule and plant load factors used in the financial analyses.

In some rare situations, a country may wish to consider investing in an FOAK plant that has been developed in another country, for example because of its superior economic performance. In this case, the minimum requirement is that the country deploying the plant have domestic experience with licensing and operating other NPPs, and that the supplier of the FOAK plant provide evidence from the regulatory authority of the country of origin that the FOAK plant could be licensed for operation in the country of origin.

In all cases, but particularly when considering an FOAK plant, it is important to clarify the expectations of the regulatory authority in the adopting country and to come to an informed judgment that these can be met before making a final commitment.

Evidence that a plant has been/can be licensed in the country of origin is a necessary condition, but does not remove completely the risk associated with the regulatory process. Thus, the purchaser may seek evidence that the supplier understands the regulatory requirements to be met in the country of deployment and that the supplier has a plan to manage this regulatory process and its attendant risks. In general, regulatory problems lead to project delays and hence cost overruns. So, regulatory risks to the customer can be offset in contractual arrangements, for example by imposing penalties for late project completion.

In the following, the fourth acceptance limit AL3.1.4 (Technology development) is discussed.

Acceptance limit AL3.1.4: For technology development: Plan to address regulatory issues and the costs included in development proposal. Throughout the development process the development team needs to keep in mind that prospective customers will want evidence that the regulatory authority in the developer's country would be prepared to license an FOAK plant. Usually, the FOAK plant would be constructed in the developer's country and the development team should assume that this will happen. Thus, the team needs to have a plan for ensuring that regulatory issues are identified and addressed, as discussed above. In fact, resolving regulatory issues often play a major role in defining the overall development plan. Thus, an economic assessor looking at investment in development needs assurances from the development proponent that such issues have been identified, a plan has been developed to address them, and that the cost of the necessary development work has been estimated and has been included in the estimate of total development costs. Hence, once development has proceeded to the point of committing to an FOAK plant, all major technical issues should be resolved and there should be no unresolved technical issues that would prevent a construction license being issued.

4.4.2. Criterion CR3.2: Experience with construction schedule

Indicator IN3.2: Project constructions and commissioning times used in economic analyses.

Acceptance limit AL3.2: Times for construction and commissioning used in economic analysis are sufficient accurate, i.e. realistic and not optimistic.

4.4.2.1. Indicator IN3.2: Project construction and commissioning times

When considering indicator IN3.2, the following should be noted: Project delays lead to cost overruns, particularly in project management and engineering support costs and in IDC. The greatest impact of project delays, particularly on IDC, arises during construction and commissioning. Thus, the time taken to construct new facilities and to bring them into operation (and so to start generating revenue) should be as short as practicable and specific targets can and should be set as development objectives.

In assessing the time taken to design, construct and commission an NPP, it needs to be recognized that front end design work, environmental assessment, and licensing applications, while potentially lengthy, represent a relatively small investment compared with the investment required to procure, construct, install, staff and commission new facilities. Commissioning comes at the end of the process when the majority of investment funds have been expended and when the rate at which interest during construction accumulates is largest so it is important to minimize the duration of commissioning.

4.4.2.2. Acceptance limit AL3.2: Construction and commissioning times

As shown below, the acceptance limit AL3.2 of CR3.2 can be divided into four different categories depending on the situation, i.e. it is adapted to the situation in a country planning to install its first NPP, additional units and an FOAK (AL3.2.1, AL3.2.2 and AL3.2.3, respectively) and for the case that a technology developer is planning to develop a NES (AL3.2.4).

The acceptance limits AL3.2.1 (first NPP) and AL3.2.2 (follow-up units) are discussed below.

Acceptance limit AL3.2.1: For deployment of the first few NPPs in a country. Construction schedule times used in financial analyses have been met in previous construction projects for plants of the same basic design.

Acceptance limit AL3.2.2: For deployment of additional units of the same basic type of NPP. Construction schedule times used in the financial analysis are based on actual construction schedules achieved in previous projects in the country.

The financial risk associated with potential project delays is minimized if the financial analyses are based on a schedule that is similar to that which has been achieved in past construction projects for plants of the same basic design. Thus, when investing in a first NPP, the project times used should reflect actual performance by the supplier with constructing a plant of the same basic design and should include contingency.

Next, the acceptance limit AL3.2.3 (FOAK) is presented.

Acceptance limit AL3.2.3: For deployment of an FOAK plant in a country with experience in operating NPPs. A convincing argument exists that the construction schedule is realistic and consistent with experience with previous NPP construction projects carried out by the supplier and includes adequate contingency.

For an FOAK plant, it will not be possible to use past experience with a plant of the same design. In this case the supplier needs to present an argument that the schedule used is realistic. This argument must include a discussion of previous experience, by the supplier, with constructing NPPs of a comparable complexity. Reductions in the duration of the project schedule, when compared with past experience, should be justified. Schedule risks should be identified and their financial consequences should be estimated when performing a sensitivity analysis (see criterion CR3.3).

Finally, the Acceptance limit AL3.2.4 (development) is discussed below.

Acceptance limit AL3.2.4: For technology development. Schedules are analysed to demonstrate that scheduled times are realistic, taking into account experience with previous NPP construction projects.

For technology development, a goal should be to reduce construction times to the lowest practical values using advanced construction techniques. Different plant designs may have different project execution times. Recent construction times for reactor projects have been as short as 52 months (first concrete to criticality) and commissioning periods from first criticality to full power have been as short as two to three months for repeat projects. Thus, a construction period of 48 months is judged to be an achievable target, for repeat reactor projects, within the near future. In due course, with innovation, use of in-shop modular construction, and for repeat plants, construction periods as short as 36 months might be achievable.

4.4.3. Criterion CR3.3: Uncertainty of economic input parameters

Indicator IN3.3: A sensitivity analysis of important input parameters for calculating costs and related financial figures of merit has been performed.

Acceptance limit AL3.3: Sensitivity to changes in selected parameters is acceptable to the investor.

The criterion requires a sensitivity analysis covering the potential range of important (economic) input parameters in postulated sets of circumstances. The indicator IN3.3 can be related to the INPRO Basic Principle in the area of economics that states that a NES to be sustainable in the long term needs to be affordable and available. Thus, the sensitivity analysis should demonstrate that acceptance limits of CR1.1 (LUEC) and CR2.1 (financial figures of merit) will still be met under different (economic) market conditions and so ensure that nuclear energy will be available and affordable under these different market conditions.

4.4.3.1. Indicator IN3.3: Sensitivity analysis

Indicator IN3.3: A sensitivity analysis of important input parameters for calculating costs and financial figures of merit has been performed.

A sensitivity analysis can be performed rather easily using NEST, which is presented in Appendix II.

For relative costs based on LUEC, the sensitivity of the ratio C_N/C_A should be studied for changes in the discount rate, overnight capital costs, construction time, and plant lifetime assumed in the calculation, and fuel costs, changes in the cost of fuel the nuclear plant and for the alternative competing technology. Here it may be noted that the high capital cost of nuclear makes its LUEC sensitive to the discount rate, while the LUEC for fossil fuel plants tends to be relatively more sensitive to fuel costs [13].

The sensitivity of the relevant financial figures of merit IRR, ROI and NPV — should be determined for changes in overnight capital costs, load factor, construction schedule, plant lifetime, availability of plant, fuel cost, and NPV, and additionally for changes in the discount rate.

For the critical input parameters, a range of possible values has to be specified. The range of variation of the parameters affecting the values of the economic indicators should not be unrealistically large to avoid being overly cautious, but should also not be unduly restrained. In the case of a design under development, it is evident that the higher the maturity of a design the lower the uncertainty of its economic input parameters. Thus, it is expected that the range of possible input values will be larger for an innovative design compared with an evolutionary design. If, in addition to the range of possible values, the corresponding probability is also available, one carry out a probabilistic analysis producing a distribution of LUEC, IRR, etc. Such an analysis would provide additional insights to the user. The aim of such a sensitivity study is to understand how changes in modelling assumptions impact the economic analyses, to obtain a good understanding of the relative importance of various factors and associated risks.

The INPRO methodology is an assessment method and does not include analysis per se. Nonetheless, the INPRO assessor needs the result of such analyses. The result of the sensitivity analysis is a case in point. In this case the assessment team might perform the analysis itself using NEST, or it could seek to obtain the information from the designer/developer of the NPP, or from other experts, e.g. the IAEA.

The results of such a sensitivity analysis should be presented so that the sensitivities of LUEC and the financial figures of merit to changes in the values of the parameters of interest are clear. For most, if not all projects, various risk contingencies are included in the project cost and schedule estimates. Such a sensitive study can be used to test the adequacy of such contingencies and/or to see the impact on economic parameters. For example, how does a delay in the project schedule of the NPP impact the cost of C_N relative to C_A?

4.4.3.2. Acceptance limit AL3.3: Sensitivity to changes

Acceptance limit AL3.3: Sensitivity to changes in selected parameters is acceptable to the investor.

AL3.3 is met if the results of such a sensitivity analysis are available to the assessor and if the sensitivity to changes in selected parameters is acceptable to the investor. Acceptable sensitivity means that the overall result of the economic assessment is not reversed, e.g. that a small increase in construction time does not make nuclear power non-competitive against an alternative energy source.

4.4.4. Criterion CR3.4: Political environment

Indicator IN3.4: Long term political commitment to a nuclear option.

Acceptance limit AL3.4: Commitment sufficient to enable a return on investment.

In assessing the risk of investment in nuclear energy systems the 'political climate' or environment in a country should be considered to determine whether there is political support for nuclear power, and whether such support is likely to be sustained. Information on the political climate is needed for an assessment based on the INPRO methodology area of infrastructure.

The issue of the political climate is presented in the area of economics primarily to ensure that an assessment in the area of infrastructure has been carried out and that this assessment has established that the political climate is favourable. Thus, if this issue has been addressed AL3.4 is met.

If such an assessment has not been done, the assessor in the area of economics should conclude that the investor is faced with an unknown and important risk that needs to be addressed by the proponent of the project. It is not the responsibility of an economic assessor to judge the political climate but rather to ascertain that the issue has been addressed.

4.5. USER REQUIREMENT UR4 (FLEXIBILITY)

User requirement UR4: Innovative nuclear energy systems should be compatible with meeting the requirements of different markets.

This requirement is directed primarily at a technology developer/investor and relates to the ability to recover development investment.

Given the uncertainty about the future, ideally, an innovative NES (which includes evolutionary and innovative designs of nuclear facilities) should be sufficiently flexible to be able to evolve and adapt in a manner that provides competitive energy for as wide a range of plausible futures and markets as possible. So, in deciding whether to develop an innovative NES, or a NES component, the developer would be expected to examine whether and how that component might be adapted to different markets or changing market conditions, recognizing, for example, that a given design of reactor would not be expected to meet the needs of all markets. Adaptation of a NES, for example, to accommodate different size modules, or to accommodate different fuels, would usually require additional investment. So, the more markets where a given component could be sold, with only relatively minor changes, the greater would be the attractiveness of developing the component and the greater would be the expected contribution that the component could make meeting the global energy needs of the 21st century in a sustainable manner, the principal objective of INPRO.

While it is easy to ask for such flexibility, there can be inherent limitations that need to be taken into account. For example, designing and licensing a reactor is a costly exercise and changing the design to modify its output is not easy. To date, economy of scale has resulted in larger and larger size units being designed and developed to the state of being commercially available. Such units are not suitable for small grids, and operating them at less than full power is not economically viable. Thus, various developers are looking at smaller modular units which, if brought to the state of proven technology, will offer a considerable degree of flexibility. But designers of larger units can consider other degrees of flexibility to adapt to a changing world. Once such example is the ability to accommodate different fuels, e.g. higher burnup fuels, MOX fuels, recycling of uranium (RU) from reprocessing LWR fuel in CANDU reactors. Much has already been done in this area. Another example is taking advantage of possible synergies between different types of reactors, which has already been the subject of two INPRO studies [18, 19]. On the other hand, when designing new fuel cycle facilities, there may be more flexibility in adopting module construction techniques to offer the ability to increase production capacity in a staged manner or to adapt the facilities to the production/reprocessing of different fuel types. The ongoing INPRO Synergies Project and similar studies may identify the best potential for further developments to achieve flexibility of future NES.

INPRO methodology has defined one simple criterion for UR4 (Table 6).

TABLE 6. CRITERION FOR USER REQUIREMENT UR4

User requirement	Criterion	Indicator (IN) and acceptance limit (AL)
UR4 (Flexibility): Innovative nuclear energy systems should be compatible with meeting the requirements of different markets	CR4.1: Flexibility of innovative designs	IN4.1: Are the innovative NES components adaptable to different markets? AL4.1: Yes

4.5.1. CR4.1: Flexibility of innovative designs

The designer of an innovative facility (reactor or fuel cycle facility) should make sure that the new design is as flexible as possible for sale under different market conditions. Examples of how to increase the flexibility of a design have been presented above.

Given the uncertainty about the future, as reflected, for example, in the wide range of possible future scenarios considered in the SRES (see Ref. [20], ideally, an innovative NES should be sufficiently flexible to be able to evolve and adapt in a manner that provides competitive energy for as wide a range of plausible futures and markets as possible. So, in deciding whether to develop an innovative NES, or a component thereof, the developer should examine whether and how that component might be adapted to different markets or changing market conditions, recognizing that a given design of reactor would not be expected to meet the needs of all markets. Adaptation would usually require additional investment. So, the more markets where a given reactor can be sold, with only relatively minor changes, the greater would be the attractiveness of developing this plant and the greater would be the expected contribution that the plant could contribute to meeting the global energy needs of the 21st century.

Decision on investing in the development of an innovative NES

The ability to adapt specific components of an innovative NES, as well as the overall adaptability of the system, for example, to accommodate different size modules, to accommodate different fuels, to meet different energy applications, and to meet the needs of different countries/regions is desirable but is not considered to be essential.

4.6. EXTENDING AN ECONOMIC ASSESSMENT TO FACILITIES OF A NES OTHER THAN THE NPP

The INPRO methodology in the area of economics assesses the competiveness of nuclear power generating electricity in a country in comparison to other available energy sources. Thus, the assessment is focused on an NPP. Other facilities of a NES are dealt with by considering the costs, to the operator of the NPP, for the products/services produced in the other nuclear facilities. This is a reasonable approach when making a decision to use nuclear energy to meet a national (or even regional) need and when one is dealing with an evolutionary design of an NPP. The NPP is the unit that produces the final energy product (heat or steam or electricity) needed by the customer and this product is to compete with alternative energy sources.

If the *reactor is of proven design*, the other components of the NES needed to operate the NES can be assumed to exist (except for disposal facilities for used fuel/and high level waste) and the cost of their products should be known.

To assess the economics of *developing an innovative design* of a NES that requires not only investment in the NPP but also investment in new processes for fuel supply and fuel processing, the investment in developing these new processes must also be considered. One approach is to look at the investment needed to develop each innovative process and at the cost of constructing and operating the facilities, once the process is developed, and so arrive at the price of the product. This can then be translated into fuel cost for the NPP, and hence a contribution to the levelized discounted cost of the energy produced by the NPP. This would then be compared with the LUEC for the available alternative energy source.

4.6.1. Checking the economic viability of adding domestic fuel cycle facilities

In the INPRO methodology, the term ‘nuclear energy system’ includes the complete spectrum of nuclear facilities (components) that comprise the nuclear fuel cycle, including front end facilities (mining, milling, refining, conversion, enrichment, fuel fabrication), as well as back end facilities (spent fuel storage, reprocessing, repository), and the reactor itself.

To perform an economic assessment on whether to install a fuel cycle facility of a NES domestically[5] [16, 21], the following information needs to be considered:

- The production unit (e.g. U ore, UF_6, UO_2, fuel cladding, fuel element, etc.), i.e. the output of the facility.
- The amount of production planned, e.g. the amount required for a national NES in terms of tonnes of U_{nat}, etc.
- The cost of each production unit generated domestically, and the price of the production unit available in a global market.
- The anticipated cost evolution of the production unit, if it is applicable.

To calculate the levelized cost (minimum price) of the production unit that covers all levelized costs of installing and operating a domestic nuclear facility, the following data are needed as input for the calculation: overnight capital cost to construct the facility; O&M cost covering staffing, cost for input materials (such as UF_6), waste management cost, and provision for decommissioning; time distribution of each payment (capital, and O&M) needed to install and run the facility; and the discount rate.

To justify the deployment of a nuclear fuel cycle facility in a country (other than the nuclear reactor) on economic grounds, the cost of each product (e.g. uranium ore, UF_6, fuel element, etc.) of a domestic facility to be installed should be competitive with the same product available outside the country.

4.6.2. Non-electrical application of nuclear power

As stated in Ref. [22] “Following successive General Conference Resolutions since the mid-eighties, the IAEA has continued to promote nuclear desalination and has been providing its Member States with the publication of guidebooks, technical documents and computer programs on nuclear desalination as well as the provision of technical assistance through the framework of technical cooperation programs.”

[5] An assessment performed by Argentina of the economic viability of installing domestic fuel cycle facilities is described briefly in Ref. [21].

One of the main goals of these activities is to determine the economics of desalination, i.e. the costs of water produced in different types of desalination plants using either heat (steam) or electricity from an NPP in comparison to non-nuclear energy sources such as fossil fuels (coal, oil, gas), and renewables (photovoltaic, and electricity from a grid).

To calculate the water costs produced in different types of desalination plants, such as multistage flashing (MSF), multi-effect distillation (MED), reverse osmosis (RO), and hybrid options (RO-MSF, RO-MED), a code was developed called DEEP (Desalination Economic Evaluation Program [23], which is available cost free to IAEA Member States [24]. The code needs technical and economic data of the energy source and the desalination plant. In case an NPP is used as an energy source for a coupled desalination plant, the main economic input data for an NPP are: specific costs of construction, operation and maintenance; fuel, and decommissioning of the NPP; and the discount rate. The main technical data of the NPP plant needed in DEEP are: Thermal and net electrical output; availability (planned and non-planned outages); and lifetime and construction time. DEEP uses a levelized cost model in a comparable manner as proposed for the INPRO methodology and incorporated in the NEST code.

The main difference between DEEP and NEST regarding the calculation of the LUEC of an NPP is the level of detail on how to determine the fuel cost of nuclear fuel cycles. In DEEP, these data are inputted, whereas in NEST for several different fuel cycles (open, partially closed and fully closed) these data are calculated for all stages of a fuel cycle (mining to waste disposal) based on detailed input information.

In addition to nuclear desalination, the IAEA has recently developed and released a code called HEEP (Hydrogen Economic Evaluation Program) that covers the production of hydrogen using an NPP and non-nuclear energy sources in a similar manner as in DEEP; this program is also available cost free to IAEA Member States [24].

Thus, the economic models DEEP and HEEP can be used to extend the INPRO methodology in the area of economics for non-electrical applications of nuclear power by using the output of NEST for a specific NPP with a defined fuel cycle as input for DEEP or HEEP.

Appendix I

BACKGROUND OF IMPORTANT ECONOMIC TERMS

I.1. DISCOUNT RATE

The discount rate is an input parameter to calculate levelized costs. This rate takes the time value of money into account, i.e. money earned in the future has less value than received today. An appropriate *discount rate* has to be selected by an economic analyst[6] to be used for the market that the analyst is considering for deployment of an NPP. The analyst has to determine and gather the information needed to make this judgment. If the analyst is from a utility (the future owner/operator of the NPP), he/she would have ready access to this information. In other situations, the analyst might need the assistance of a specialist who is knowledgeable about the capital markets in the country or region in which the NPP is to be deployed.

As shown in many studies, the results of an economic assessment, and particularly the cost comparisons between energy alternatives, can be sensitive to the discount rates used. The choice of a discount rate for decision making by a given analyst will depend on its specific situation and the overall economic, regulatory and commercial framework of the country. Although there is extensive published literature on discount rates and their relationship with financial risk and required rates of return for private or public investor, there is no consensus view on the matter (see Ref. [25]).

As a rule of thumb, real discount rates for a government owned utility in a regulated market could be expected to vary in the range from about 3–5%, for a private sector utility operating in a regulated market from about 5–10%, and for a private utility operating in a deregulated market from about 10–15%[7].

The value of the discount rate is linked to the interest that an investor has to pay for long term bonds, i.e. in the case of the government as investor the discount rate used should not be lower than the interest the country has to pay on its long term bonds.

I.2. LOAD FACTOR AND ANTICIPATED PLANT LIFETIME

Load factor and anticipated plant lifetime are important since they determine how capital costs are accounted for. A constant (plant life average) load factor might be used, or a time dependent load factor might be used to reflect time dependent factors such changes in thermal efficiency resulting from changes in fouling factors, clearances, etc. The approach to be followed will depend on the information available to the assessor and on the level of detail that the assessor wishes to include in the assessment. However, to be consistent, when a given factor associated with plant ageing is taken into account for a nuclear plant in a given assessment, similar ageing effects should be included for the alternative energy sources, such as the decrease in the efficiency of gas turbines resulting from blade erosion, combustion chamber depositions and debris, etc. The aim is to make an unbiased comparison of equivalent costs.

I.3. COSTS FOR GENERATING ELECTRICITY

The costs for generating electricity are usually divided into capital investment (CI) costs, operating and maintenance (O&M) costs and fuel (F) costs. Information on CI, O&M and F costs and on the timing of such expenditures, over the plant lifetime, should be provided by the (potential) supplier(s) — based on a cooperation agreement — to the analyst, who can then discount them using an appropriate discount rate to determine the NPV

[6] The term ‘analyst’ is used here to distinguish it from the term ‘INPRO assessor’. The analyst is supposed to calculate the necessary inputs such as LUEC for the assessment to be carried out by the assessor.

[7] In Ref. [5], the GIF EMWG proposes two different discount rates, namely 5% and 10% for an economic assessment of an NPP under development. The 5% is to be used for a utility operating in a regulated market, where revenues are guaranteed by captive markets, the 10% is to be used for deregulated markets, where the plant must compete with other sources of generation for revenues.

of these costs, and hence the LUEC. As noted above, it is the responsibility of the analyst to determine the discount rate to be used.

For simplicity, a useful approximation is to assume that the *amortization time* over which costs are recovered from revenues for a given plant is the plant lifetime. This avoids the complexity associated with power upgrading and updating that might be undertaken for a plant that has already been fully amortized. But requirements for and the costs of back fitting that are foreseen to be undertaken during the plant lifetime need to be taken into account. This is especially important for technologies with relatively short durations between necessary major refurbishments, such as gas turbines or wind turbine technologies.

After fixing the time base for all the calculation of an economic assessment, all the costs, obtained from different sources need to be compared in *constant money terms* (see item I.6) and expressed for a reference time base. Because it is almost certain that all necessary (published) price data will not be expressed in constant money terms for the same date, appropriate currency deflationary or inflationary factors will be needed to convert cost and prices to values for the reference year. This is important when the results of an assessment using the INPRO methodology are to be compared with results from other studies, and when comparing costs between different technologies for a given INPRO assessment.

I.3.1. Investment costs

Usually, investment costs for deploying an NPP are divided into different categories as discussed below (see also Refs [8, 9]).

Direct construction costs (also called *overnight capital cost*): These costs include the cost of the plant components and materials, and the labour required for installation. Additionally, they contain costs for land and land rights, structures and improvements, plant equipment including generator and electrical equipment such as switch gear and transformers, and special materials (such as the moderator for a HWR or the coolant inventory for a lead bismuth reactor).

Contingency allowances: The plant investment should include a contingency allowance to provide for unforeseen or unpredictable costs. Often, the designer can determine an appropriate allowance item by item or as a lump value for all the direct construction costs. The contingency allowance will depend on the maturity level of the design and on gaps in engineering knowledge. It also depends on the source of cost estimation (based on ordered plants, paper analysis, quotation, feasibility study or previous experience [25]), or the degree of innovation (proven design, extrapolated design, or innovative design [26]).

Indirect construction costs: A number of indirect construction costs must be added to the direct construction cost to obtain the total plant investment. These often include the cost of contracting, design, engineering, inspection, startup, and interest during construction. Indirect costs also cover construction facilities, equipment and services, including buildings and other facilities that are removed after construction has been completed. Indirect costs also include taxes and insurance, if they are applicable (see the discussion of fiscal regimes presented in Section I.5). Costs for staff training and for plant startup as well as costs incurred by the owner in carrying out the project, such as the costs of licensing, public relations and administrative overheads are also in the category of indirect costs. Indirect construction costs can vary considerably depending on differences in accounting systems and the experience of the contractor in building a specific plant.

What is included in direct costs and in indirect construction costs can depend on contractual arrangements. In a fixed price 'turnkey' contract many indirect costs listed above maybe be included in the fixed price. Thus, care needs to be taken to ensure that all costs have been identified and evaluated but also to ensure that costs are not double counted.

Backfitting cost: This cost includes all the major refurbishment costs not included in the annual O&M costs, and required to keep the performance of the plant within declared values. Examples include costs for steam generator replacement, or, in the case of pressure tube reactors, pressure tube replacement, or, in the case of pressure vessel reactors, vessel refurbishments such as replacement of internals or annealing. The total cost for such backfitting, and the time when the capital expenditure is required, need to be included when calculating levelized generating costs, consistent with the assumed plant lifetime over which costs and revenues are levelized.

Decommissioning, waste management and waste disposal costs: The costs of decommissioning, waste management and, in particular, waste disposal, also need to be estimated and taken into account when calculating levelized costs. The costs of decommissioning and waste management, including placing the waste into its end state, are often converted to annual costs and are treated as such, either as a fuel cost or an operating cost or some combination of the two, by calculating the NPV of the funds that have to be set aside on an annual basis to cover the cost of decommissioning and residual waste management costs at the end of plant life. The costs of ongoing waste management activities, such as waste processing and interim storage of wastes, are usually included as an operating or fuel cost. The analyst should obtain information on such costs from the plant developer/supplier.

I.3.2. Fuel costs

Fuel expenses are the second major component of nuclear power costs, and the most important cost for fossil fuel plants. If, in the NES description, the assessor proposes a system with fuel fabricated or negotiated in detail inside the system (and not bought as a single item at fixed price), the analysis becomes more complicated. A detailed accounting of fuel cycle costs is relatively complicated, since a number of operations are involved and levelized costs are sensitive to the irradiation time in the reactor as well as to numerous financial and process variables.

Fuel element costs: In nuclear plants, the classical fuel costs are expressed in $/kg of heavy metal included in the fuel (uranium, plutonium or thorium), and the way to perform the assessment of such costs depends on the scope of the system. In a system with a single contract for the fuel supply during the entire plant life without any concern about external price evolution, resource depletion, etc., only the price of the final (fabricated) fuel elements and schedule for payment are needed. This approach may or may not include the spent fuel management costs.

In a detailed fuel cycle assessment, three main items are required:

— *Fuel material costs.* These include the costs of mining, milling and processing the original ore, and, for enriched fuels, the costs for enrichment and conversion.
— *Costs of manufacturing fuel elements and of processing the irradiated material.* In general, larger production volumes lead to lower unit costs so purchasing fuel from a manufacture supplying many units would be expected to be significantly cheaper than building a dedicated plant to supply a small number of units.
— *Discount rate and timing.* Since the time required for one complete fuel cycle operation could be of the order of two–six years [26], levelized costs are sensitive to the discount rate used and the timing of expenditures, and these considerations need to be specifically addressed.

Fuel loading costs. The costs for two types of fuel loadings (into the reactor) can be distinguished, namely the cost for the first reactor core and the costs for routine refuelling. The cost of the first reactor core load of fuel represents an investment that is amortized over the plant life. This fuel needs to be supplied prior to plant startup. The costs can be significant, particularly for low power density cores, high enrichment cores, or long life cores. The second cost covers the ongoing periodic expenditures for new fuel necessary to replace the losses of fissile material (e.g. uranium) by burnup due to the power generation between refuelling. The first core implies a fuel demand bigger than any refuelling demand during the plant life, and the payment needs to be done in advance of commercial operation. Thus, it can be a significant contributor to LUEC, particularly if a high discount rate is used.

Spent fuel costs and credits. Two other costs are relevant for the fuel cycle, i.e. the spent fuel management cost, and the reprocessing cost; the related high level waste (HLW) management costs need to be accounted for. In the latter case, a credit for fissile content in spent fuel may be included. Such costs include the costs for interim storage and for disposal.

I.3.3. Operation and maintenance costs

The O&M expenses include the direct and indirect payroll costs for plant personnel, the cost of special materials, makeup, e.g. of heavy water or of special coolants, and general supplies. Miscellaneous O&M costs include items such as public relations, training, rents and travel. It also includes liability insurance and the fixed charges for the working capital to pay for items in the O&M category. O&M costs are usually divided into fixed O&M costs, including those that do not depend on the energy generated each year, and variable O&M costs, including those that depend on the energy generated. Usually variable O&M costs are proportional to the annual electricity output.

I.3.4. Consistency of cost data

The approach used in INPRO methodology requires the comparison of costs and other financial data for different alternatives for investment into energy sources. Thus, it is important to use cost data that are consistent for the different types of energy systems and for different options of the same type of energy system.

Consistency of cost data can be a major challenge when the assessor is dealing with different types of technology. For example, care must be taken when comparing data from commercial facilities that have already been deployed with estimated data for a future deployment of a plant for which an FOAK has not yet been constructed. The reliability and the basis of estimating costs for the two types of facilities could be so different that, even with the best of intentions, estimates may still be biased in favour of one option or another. Another source of inconsistency could be produced when costs for different scopes of supply are classified under the same name. This type of wording mismatch could happen in the comparison of the direct cost of a nuclear reactor and a fossil fuel plant. For example, if a nuclear reactor requires a cooling tower, the cost will usually be included in the direct plant cost, but for some fossil fuel plants (e.g. some combined cycle gas turbines contracts) the cooling tower could be included as an owner's cost. Thus, it is very important to be clear about what is really included in the investment cost component for one system compared with that for an alternative.

Some authors recommend that particular care be taken when fossil fuel alternatives are considered, to be clear as to what is included in the cost of a turnkey project's scope [27]. For example, gas turbines fuelled with natural gas could require additional investment in gas pressure reduction systems, if they are supplied from a high pressure pipeline, or natural gas compressors, if the turbine is supplied from a low pressure pipeline. Gas turbines fuelled with liquefied natural gas require storage and transfer facilities. It needs to be ascertained whether the cost of such facilities are included in the fuel price or in the project investment or have not been included.

As well, what is included within the definition of direct cost could change from one technology to another. For example, some technology suppliers could include the cost of the condenser in the direct cost, but it may not be included in the published data of a supplier of a different technology.

Standardized accounting systems are available for nuclear power plants. The IAEA has developed a well known comprehensive accounting system capable of addressing a wide spectrum of costs [8, 9]. Some countries use their own cost accounting system [28]. For INPRO methodology, only a very simple cost definition is required, so a very broad definition will be used based on recommendations documented in Ref. [29].

I.4. FINANCIAL FIGURES OF MERIT

Levelized unit energy costs are recommended in the INPRO methodology to be used for comparing energy costs. However, other financial figures of merit are needed to perform an INPRO assessment in the area of economics, for example to evaluate the profitability of investment and hence its attractiveness.

To calculate the profit produced by the electricity generation, two different types of financial figures could be used, and different data are required:

— *Undiscounted profit measurement*: Using real values for measuring profitability without using the levelized concept, several figures could be used, such as *payback time* or ROI. In the current version of the INPRO Manual, ROI is used. To do so, requires the value for the PUES. The method of calculating the PUES may vary between Member States. In some Member States, it may be obtained by modelling the grid load dispatch from published values for the grid, or by comparison with other active generation plants costs in the grid.

— *Discounted profit measurement:* Using real values, the classical figures for the discounted profit calculation is either IRR or NPV of profit. For both of them, the only additional variable is the reference PUES, as is required by ROI. So they could be easily used by INPRO. As the INPRO methodology provides some reasonable flexibility in selecting economic indicators, both NPV and IRR will be used.

These figures of merit are not unique, and the INPRO assessor could define his or her own figures of merit depending on the country or company investment policy. For example, a country interested in nuclear energy as an introduction of a 21st century technology will be interested in the total levelized investment. Such a country might compare investing in a small power reactor in competition with investing in a research reactor.

To calculate the PUES, state of the art computational tools, such as MESSAGE, WASP or BALANCE, could be used [4]. As well, simple price estimation methods could also be applied, depending on the scope of the assessment and the expertise and time commitment of the assessor.

To use computer codes to calculate PUES requires judgment with regard to the use of the results to be obtained from the assessment. Different codes have been developed with different objectives utilizing different approaches to model a complex reality. The codes available tend to be more complementary than an alternative. Some codes have been programmed in order to simulate long term energy evolution; others have been developed for short term very detailed modelling.

Thus, expert judgment needs to be applied when an assessor wants to use complex codes and modelling. International agencies and institutes, such as the IAEA can provide assistance to help interested code users in energy studies and planning.

I.5. FISCAL REGIMES

Fiscal regimes, including for example taxation policies, central bank rate policies, exchange rate policies, have a significant impact on the calculated generating cost of electricity. These vary from country to country and also on a local, national, and regional basis. As shown in Ref. [30], the introduction of simulated harmonization of fiscal regimes has not been possible and only a common very high level fiscal regime policy could be considered, for example a special tax or insurance for a given technology, etc. The calculations of generating costs usually are carried out without income and profit taxes because such taxes do not affect the relative competitiveness [31] of different energy sources. On the other hand, taxes on fuels, emissions and plant specific taxes that may differ from plant to plant should be included in the cost if they are relevant for the assessor.

I.6. CONSTANT AND CURRENT MONEY TERM

Cost elements could be expressed in constant or current money terms. Current money means money as spent or earned. Future payments in current money are calculated using nominal inflation and nominal interest rates. Constant money means money of constant value, i.e. ignoring inflation. Future payments in constant money are calculated using real escalation and real interest rates [9].

Cost elements used in the calculation of the generating costs of power plants are normally expressed in constant monetary terms, as it is generally accepted that calculations performed in constant money are best suited for comparison. So, no inflation correction needs to be included in time dependent cash flows and variation in future prices of the components are considered as a drift in the constant money price. Hence the so-called real discount rate needs to be used for present value calculations.

I.7. CURRENCY EXCHANGE

The choice of a common currency unit is essential when different economic data sources are used for different components and systems in a given NES and for alternative technologies. The assessor should be extremely cautious in comparing cost data from different countries even when they are expressed in a common monetary unit. Usually, the use of constant prices properly accounts for most deviations, but as pointed out in several studies [31], exchange rates do not necessarily reflect purchasing power parities accurately, and so their use might affect cost comparisons between countries in a way that does not correspond to actual cost differences.

I.8 PRICE SETTING

Usually, the costs discussed in the INPRO methodology will refer to the cost of new power supplied to the station bus bar, where electricity is fed to the grid. Thus, it would exclude costs of transmission and distribution to end users. But, for some energy scenarios the cost to transport electricity may need to be included in the assessment in order to study, e.g. the advantages and disadvantages (trade-off) of small and medium size, dispersed power systems compared with large centralized plants. While such an issue is usually not considered in economic assessments (Refs [30–33]) it could be relevant for some assessors.

I.9. SOURCE OF CAPITAL

In many countries, domestic savings are the main source of capital for infrastructure projects, including energy and electricity infrastructure. The availability of domestic capital will be most constrained in developing countries. Even where domestic savings comfortably exceed the energy sector's demand for capital, energy companies will still have to compete with other sectors for domestic financial resources. In addition, energy investment may involve large projects, even mega projects, and in such cases the excess of domestic savings over energy investment requirements could be much smaller. Furthermore, domestic savings need to be mobilized through financial markets.

The shortfall between investment requirements and domestic savings in some countries highlights the need to mobilize capital inflows from abroad, especially from developed countries, where domestic savings exceed investment. Dependence on external financing brings both benefits and risks. Financing from abroad often reduces the cost of capital and provides longer debt maturity. At the same time, overdependence on foreign investment flows can strain a national economy, large capital inflows can affect exchange rates, and future currency depreciations would increase the debt burden.

Energy projects are usually more capital intensive than projects in most other industries and often involve large initial investments before production can begin. The electricity sector is the most capital intensive of all the major industrial sectors, measured by capital investment per unit of value added [34–37]). The more capital intensive an industry, the more exposed it is to financial risks such as changes in interest rates and other events in financial markets. Energy investments are exposed to differing types and degrees of risk, with consequences for the cost and allocation of capital. The higher the risk associated with an investment, the higher the cost of capital and the higher the return required by investors and lenders.

Profitability is the key factor in company's ability to raise funds for investment, whether on a corporate or a project basis. If the capital employed in a company is not generating an adequate return (measured in its own criteria) the company will have limited access to new capital.

Appendix II

THE NESA ECONOMIC SUPPORT TOOL

This appendix presents background and general formulas on how to calculate electricity generation costs in accordance with the INPRO methodology, followed by the content and the equations used in NEST (available, on request, from the IAEA/INPRO Secretariat).

II.1. POWER GENERATION COST METHODS

This section describes the approach and provides a set of equations to calculate the generation costs, and highlights the main parameters needed for the calculation. It provides some important general definitions, but does not discuss in detail all of the concepts.

There are several methodologies available for calculating power generation costs [8, 9, 26, 38]. The IAEA report [8] includes a software package called BIDEVAL-3 to calculate power generation costs, with a set of computer programs for use on a PC. The adoption of standardized methodology for cost calculation is a prerequisite for fair comparison among different electricity generation options. So it is very important to define a well accepted method in order to produce useful and unbiased results.

For economic comparison of different types of power plants in a general framework, particularly with a small amount of additional detailed information like bond emissions, equities and other financing tools, calculating the LUEC, sometimes called levelized lifetime cost or levelized electricity generation cost, is very useful. LUEC was used in many comparative assessments [30–33, 39], and is particularly suitable for the INPRO methodology, assessing the relative competitiveness of different energy sources.

II.1.1. Time value of money

In the evaluation of engineering projects involving expenditures of funds, costs and receipt of revenues such as during the construction of electricity generation plants, all at different times, a systematic treatment of the effect of the time variable value of money is required. The value of money can be considered to change as it moves through time. In the present, for example, for an investment company money has a greater value than it would have in the future because it can be used for another investment project in the interim. This investment could produce revenues and later the funds could be available again with some profits for a second investment project.

The present value concept provides for the shifting of money from one time to another, with a corresponding shift in the value. If a given amount of money A_1 is delayed for a given time drift, the value of the money A without such delay is smaller to the initial value, so A/A_1 is a constant number less than 1, usually called the discount factor, and represents the decrease of value due to the time drift; this constant number could be written as $1/(1+r)$ where r is written as a rate, and is called discount rate, defined by:

$$A = A_1 \cdot \left(\frac{1}{1+r} \right) \quad (1)$$

The value of the money referred to the initial time, or actual value, is usually called present value of the money when the reference time is taken at the present time of the project. As the base time of a project could be defined arbitrarily by using negative and positive time values, the levelized value is the present value in a specific time base obtained applying the discount rate.

If the time drift is a single year, the discount rate is called the annual discount rate, and is the standard unit for evaluating the decrease of worth of the money for a time delay.

It could be easily shown, by successive application of Eq. (1), that the present value of a given A_n amount of money after n time periods could be written as:

$$A = A_n \cdot \left(\frac{1}{1+r} \right)^n \quad (2)$$

The levelized value S of any arbitrary time distribution of money A_i to the base time t_0 could be calculated as the summation of the individual levelized values of each amount of money referred to t_0, using Eq. (2):

$$S(t_0) = \sum_{t=t_{START}}^{t_{END}} \frac{A_t}{(1+r)^{t-t_0}} \tag{3}$$

The discount rate that is appropriate for the power sector may differ from country to country, and in the same country could be different from utility to utility. The discount rate could be related to the returns that could be earned on typical investment for the same players; it may be a rate required by public regulators incorporating allowance for financial risk and/or derived from national macroeconomic analysis. It may also be related to other concepts like the tradeoff between costs and benefits for present and future generations.

It is important to stress that as the levelized value is the value of the money for an investor, the value needs to be computed without inflation, called real values, because the price increase by inflation does not produce additional capacity to buy or to pay for services or goods.

In a project with incomes and expenditures, the levelized cost methodology discounts the time series of expenditures and incomes to the present value in a specific base year by applying a discount rate. Cost elements used in the calculation are expressed in real values or constant monetary terms.

To build and operate a power system, a specific cash flow for building, fuelling, operating and dismantling the plant, including waste management and refurbishment needs to be considered. The levelized value of the expenditures $E(t_0)$ could be written using Eq. (3):

$$E(t_0) = \sum_{t=t_{START}}^{t_{END}} \frac{CI_t + O\&M_t + F_t}{(1+r)^{t-t_0}} \tag{4}$$

with:

CI_t = Capital Investment expenditures at year t;
O&M_t = O&M expenditures at year t;
F_t = Fuel expenditures at year t;
t_0 = a point in time t_0 which all costs are to be discounted to;
t_{START} = beginning of project (start of the first construction period);
t_{END} = end of the project (for a single unit consideration t_{END} is the lifetime of plant).

Capital investment expenditures need to be scheduled on a yearly basis, including overnight capital cost, interest accrued during construction period, contingency cost, owners cost, backfitting, and decommissioning cost.

O&M include all costs borne by producers (utilities) that do not fall within investment and fuel cost. Some of them are costs that need to be paid independently of the electricity generated and are called fixed costs; others are costs that depend on the electricity generated each year and are called variable costs. O&M costs usually include the plant radioactive waste management costs and taxes with the exception of spent fuel management services outside of the plant (long term storage, reprocessing, disposal, etc.).

Fuel expenditures need to be scheduled on a yearly basis. For NPPs, an important cost needs to be paid previously to reach the first criticality in order to have enough reactivity excess to generate the electricity up to the first refuelling. As this first core reactivity is needed up to the end of the operational life, the first core cost is usually called first core amortization, as distinguished from the refuelling cost, required to produce the energy produced each year. Fuel expenditures need to consider all the front end costs, together with the back end costs.

Special care needs to be taken to avoid double counting some costs, for example refurbishment, because if it is included in the capital costs, it does not need to be added in the O&M. For heavy water nuclear reactors, some countries put the first load of heavy water in the capital expenditures and annual replacement in O&M, and other countries put all the heavy water expenses in O&M.

When a nuclear system produces commercial electricity, the net power is supplied to the busbar stations, fed into the grid and produces income from selling the power. Net power does not include the house load or internal power used in the plant itself. The levelized value of gross income $GI(t_0)$ by selling the electricity could be written using Eq. (3):

$$GI(t_0) = \sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^{t-t_0}} \cdot R_t \tag{5}$$

with

P_t = Net electrical power of the nuclear system under consideration at year *t;*
8760 = Total number of hours in a year;
Lf_t = Load factor of plant in year *t;*
R_t = Electricity busbar price in year *t* (in a general case it is a time dependent value).

II.1.2. Levelized unit energy cost

If we look for a price of electricity which would have to be paid by consumers to repay exactly the levelized expenditures with the levelized gross income, i.e. the cost of electricity C_t — Eq. (5) — is to be equalized to gross income — Eq. (4):

$$\sum_{t=t_{START}}^{t_{END}} \frac{CI_t + O\&M_t + F_t}{(1+r)^{t-t_0}} = \sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^{t-t_0}} \cdot C_t \tag{6}$$

Equation (6) indicates that there is an unlimited number of the time dependent solutions C_t. Assuming that during the plant lifetime the cost of electricity *C* produced will be constant, one gets a single, unique constant cost of electricity *C* for a given discount rate *r*, defined by Eq. (7):

$$\sum_{t=t_{START}}^{t_{END}} \frac{CI_t + O\&M_t + F_t}{(1+r)^{t-t_0}} = C \cdot \sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^{t-t_0}} \tag{7}$$

The value of *C* is independent of the time base t_0, and equals:

$$C = \frac{\sum_{t=t_{START}}^{t_{END}} \frac{CI_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} \tag{8}$$

C in Eq. (8) is the LUEC, defined as the costs per unit of electricity generated, which is the ratio of total lifetime expenses and the total expected output, expressed in terms of present value equivalent. LUEC is equivalent to the average price that would have to be paid by consumers to repay the investor (utility) exactly the expenditures for capital, O&M and fuel, with a proper discount rate.

The divider in Eq. (8) could be split into the three main terms, capital/O&M/fuel, in order to obtain:

$$\frac{\sum_{t=t_{START}}^{t_{END}} \frac{CI_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} = LUAC \tag{9}$$

LUAC is the levelized unit life cycle amortization cost;

$$\frac{\sum_{t=t_{START}}^{t_{END}} \frac{O\&M_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} = LUOM \tag{10}$$

LUOM is the levelized unit life cycle O&M cost;

$$\frac{\sum_{t=t_{START}}^{t_{END}} \frac{F_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} = LUFC \tag{11}$$

LUFC is the levelized unit life cycle fuel cost.
The summation of all the three costs gives LUEC:

$$LUEC = LUAC + LUOM + LUFC \tag{12}$$

II.1.3. Net present value

LUEC is not the only financial figure of merit for an investment project and has some limitations, as discussed in Section 4.2.1 (Indicator IN1.1: Cost of energy). Thus, consideration only of LUEC does not cover all economic aspects of a planned project. For this purpose, other financial figures of merit are defined, e.g. NPV, IRR, ROI and others. These financial figures of merit could be calculated in case price estimation is available.

The difference between incomes and expenses produces the net benefit. During the construction period there is no net income, and the investment produces a negative benefit, after startup a positive profit is produced during the plant's lifetime. This will produce a time dependent profit or net income that could be levelized using a discount rate. For a power plant project, this levelized net income $NI\ (t_0,r,R_t)$ discounted at a rate r and at time t_0 is equal to the difference between Eqs (4) and (5):

$$NI(t_0,r,R_t) = GI(t_0) - E(t_0) \tag{13}$$

The levelized net income *NI* is also called net present value (NPV) at time t_0 for the investment project and by definition is equal to Eq. (14):

$$NPV(t_0,r,R_t) = \sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^{t-t_0}} \cdot R_t - \sum_{t=t_{START}}^{t_{END}} \frac{CI_t + O\&M_t + F_t}{(1+r)^{t-t_0}} \tag{14}$$

If the electricity price is constant in terms of 'real money' (i.e. without inflation), a constant reference price per unit of electricity sold to the customer, which is called *PUES*, may be introduced to simplify Eq. (14) as follows:

$$NPV(t_0,r)=PUES\cdot\sum_{t=t_{START}}^{t_{END}}\frac{P_t\cdot 8760\cdot Lf_t}{(1+r)^{t-t_0}}-\sum_{t=t_{START}}^{t_{END}}\frac{CI_t+O\&M_t+F_t}{(1+r)^{t-t_0}}=$$
$$=\left(PUES-\frac{\sum_{t=t_{START}}^{t_{END}}\frac{CI_t+O\&M_t+F_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}}\frac{P_t\cdot 8760\cdot Lf_t}{(1+r)^t}}\right)\cdot\sum_{t=t_{START}}^{t_{END}}\frac{P_t\cdot 8760\cdot Lf_t}{(1+r)^{t-t_0}} \tag{15}$$

Using Eq. (8), we can get a simplified equation for the NPV calculation:

$$NPV(t_0,r)=(PUES-LUEC)\cdot\sum_{t=t_{START}}^{t_{END}}\frac{P_t\cdot 8760\cdot Lf_t}{(1+r)^{t-t_0}} \tag{16}$$

It is clear that if the electricity price is constant and is equal to the levelized lifetime cost, the NPV is 0 because at that discount rate, levelized income exactly equals the levelized expenses. The NPV could be taken as the levelized profit produced by the investment, if it is considered that the discount rate is the minimum rate of return or the overall cost of money to the enterprise; but it is sometimes taken at a somewhat higher value, with the argument presented that the rate of return must be above the cost of the funds or there would be no interest in the investment. In that case it needs to be taken as a necessary condition, but not as a sufficient one.

II.1.4. Internal rate of return

Another method to evaluate an investment project is the internal rate of return (IRR) method, an iterative procedure that determines the unknown discount rate that is needed to balance the stream of expenditures and benefits (income). It is similar to NPV except that now the ROR is an unknown quantity. The minimum value of return rate for a project is the IRR of that project. Then, the IRR could be defined as:

$$NPV(t_0,IRR,R_t)=\sum_{t=t_{START}}^{t_{END}}\frac{P_t\times 8760\times Lf_t}{(1+IRR)^{t-t_0}}\times R_t-\sum_{t=t_{START}}^{t_{END}}\frac{CI_t+O\&M_t+F_t}{(1+IRR)^{t-t_0}}=0 \tag{17}$$

As can be seen in Eq. (17), equalizing the NPV to 0 makes it unnecessary to refer to a time base t_0. Then, the equation for the IRR could be rewritten as:

$$\sum_{t=t_{START}}^{t_{END}}\frac{P_t\times 8760\times Lf_t}{(1+IRR)^t}\times R_t-\sum_{t=t_{START}}^{t_{END}}\frac{CI_t+O\&M_t+F_t}{(1+IRR)^t}=0 \tag{18}$$

From Eqs (8) and (18), it is easy to see that if the price is equal to the levelized lifetime cost, the IRR equals the discount rate.

Analysing Eqs (8) and (18) and using the same approach as demonstrated in Eq. (15), one can define an alternative way to define the IRR which is more convenient for calculation:

$$\begin{cases} r=IRR \\ LUEC(r)-PUES=0 \end{cases} \tag{19}$$

II.2. OBJECTIVE AND GENERAL CHARACTERISTICS OF NEST

NEST was developed to enable an assessor using the INPRO methodology in the area of economics to easily determine numerical economic parameters such as LUEC, financial figures of merit like the IRR, ROI, NPV and total investment (TI), and its limit for an assessment TI_{LIMIT}. NEST calculates these parameters for several NESs and for alternative systems, e.g. a fossil fuel power plant. The output of NEST can be used as input for an economic assessment using the INPRO methodology.

In addition, NEST enables efficient comparison of the results of different economic studies because it shows explicitly all necessary input data for calculation of the above mentioned numerical economic parameters.

This tool can also be used to calculate these numerical economic parameters for different types of nuclear reactors with different nuclear fuel cycles and for non-nuclear power plants such as fossil fuel plants. The types of reactors include thermal light and heavy water reactors, and fast reactors with different breeding ratios. The fuel cycles for thermal reactors covered in NEST include an open fuel cycle (with a once-through concept) based on uranium and a partly closed fuel cycle with spent fuel recycling (MOX), and for fast breeder reactors a completely closed cycle.

The models for treatment of MOX fuel cycles in thermal reactors and fast reactors with closed fuel cycles are based on studies performed by Harvard University [2] and the Massachusetts Institute of Technology [3].

There are four different versions of NEST (see Table 7): version 1, called the basic version, and three advanced versions. The advanced versions can be activated by the NEST user one by one consecutively and cover the NES used in the basic version (reactor with open fuel cycle), plus more advanced types of reactors (fast reactors) with closed fuel cycles and advanced fuel cycles (MOX) for thermal reactors.

TABLE 7. ENERGY SYSTEMS COVERED IN NEST VERSIONS 1–4

Energy systems covered	Version 1 Basic version [1]	Version 2 Model based on Harvard University (HU) study [2]	Version 3 Model based on Massachusetts Institute of Technology (MIT) study [3]	Version 4 Extension of Version 1 based on Harvard University study [3] for fuel cycle.
Nuclear reactor using LEU with open fuel cycle	X	X	X	—
Non-nuclear power station (fossil, hydro, etc.)	X	—	X	—
LWR using LEU and MOX fuel	—	X	X	X
FR (with BR~1) closed fuel cycle	—	X	—	X
FR (with BR>1) closed fuel cycle	—	—	—	X

In addition, some special options are available for each option, such as when investments are made within a year, how contingency costs are to be spent, and whether a depreciation tax benefit is taken into account. The default input for each version of NEST is: for the basic version 1, the input values are from the example in Volume 2 of IAEA-TECDOC-1575 [1], and for versions 2 and 3 the input values as documented in Refs [2, 3].

For convenience and following a tradition existing in such models, whenever a time base t_0 is used in the following equations, it is supposes that it coincides with the power plant instant of startup and equals 0.

II.3. NEST VERSION 1

The first version of NEST is called the ‘basic version’ and uses the model described in Ref. [1]. In this basic version, two types of water cooled thermal reactors with an open fuel cycle using uranium fuel and an alternative power plant, e.g. fossil fuelled, can be evaluated. That is, the numerical economic input parameters LUEC, IRR, ROI, NPV and total investment plus its limit can be calculated for an assessment. The open fuel cycle of the two reactors covers all fuel services of the front end needed to produce fresh fuel for the reactors, i.e. purchase of natural uranium (U_3O_8), conversion to UF_6, enrichment and fuel fabrication; it also covers the back end of the open fuel cycle, i.e. storage and disposal of radioactive waste and spent fuel.

All values in NEST are discounted to the power plant startup (in the case of cost calculation for several units, to the startup of the first unit).

In the following, the equations for LUEC, IRR, ROI, NPV and total investment are presented. First, the equations for an NPP will be discussed, followed by the ones for a fossil fuel power plant.

II.3.1. Calculation of LUEC for an NPP

The LUEC (mills/kW·h) (Eq. (12)) includes three factors: the capital costs (LUAC), the O&M costs (LUOM) and the fuel costs (LUFC). LUEC is defined as the cost per unit of electricity generated, i.e. the ratio of total lifetime expenses to total expected power output, expressed in terms of a present value equivalent.

The levelized capital costs, LUAC (mills/kW·h), were defined in Eq. (9). In the NEST basic model, they are split into three terms:

$$LUAC = \frac{ONT + IDC}{Lh} + LUAC_{BF} + LUAC_{D} \tag{20}$$

$LUAC_{BF}$ (mills/kW·h) are the levelized back fitting costs and $LUAC_D$ (mills/kW·h) are the levelized decommissioning costs. The terms $LUAC_{BF}$ and $LUAC_D$ are input data to NEST. It is supposed in the NEST model that funds, which are necessary to cover decommissioning and back fitting expenses, are to be accrued uniformly during the lifetime of a reactor as a certain adjustment of the electricity cost. In this case, levelized and non-levelized parameters will coincide (a similar effect is demonstrated, in Eq. (23), for O&M cost), i.e. current non-discounted costs of these services are to be used as an input.

ONT is the total overnight cost per unit of installed capacity, including the overnight construction cost (OCC), the contingency (CC) and owner costs (OC). It equals the cost of a construction project if no interest was incurred during construction, as if the project was completed ‘overnight’. An alternative definition is: the present value cost that would have to be paid as a lump sum up front to completely pay for a construction project. OCC, CC and OC are input parameter.

IDC is the interest accumulated during the construction period of the plant and is usually equal to its capitalized interest. It is defined as:

$$IDC = ONT \cdot \left(\sum_{t=t_{START}}^{0} \frac{\omega_t}{(1+r)^t} - 1 \right) \tag{21}$$

where ω_t is a normalized distribution of funds to be invested per year of construction:

$$\omega_t = \frac{ONT_t}{ONT}$$

where is linked to *ONT* by the equation. $ONT = \sum_{t=t_{START}}^{0} ONT_t$

The time between t_{START} (negative value) and *0* (reactor startup) is the construction period T_C. Both ω_t and *Tc* are input to NEST.

$$Lh = 8760 \cdot Lf \cdot \sum_{t=0}^{t_{LIFE}} \frac{1}{(1+r)^t} = 8760 \cdot Lf \cdot \left(\frac{1 - \left(\frac{1}{1+r}\right)^{t_{LIFE}+1}}{1 - \left(\frac{1}{1+r}\right)} \right) \tag{22}$$

Lh is an intermediate parameter calculated in version 1 of NEST. In Eq. (22), Lf is the load factor, $8760 = 24 \cdot 365$ is the conversion factor of years into hours, t_{LIFE} is the lifetime of the plant, and *r* is the real discount rate; all three values are input data for NEST.

The levelized unit life cycle O&M cost, LUOM (mill/kW·h), was defined in Eq. (10). This parameter can include both the costs which are dependent on the amount of electricity produced $(O\&M)_{VAR}$, and those which are independent of plant performance $(O\&M)_{FIX}$, e.g. NPP staff salaries, auxiliary equipment and materials purchasing, refurbishment of buildings and equipment, non-fuel waste management, etc. Assuming that O&M expenses are distributed evenly by year and reactor power and load factor are also constant (i.e. $P_t = P$ and $Lf_t = Lf$) after the reactor startup, one can simplify the formula for LUOM:

$$LUOM = \frac{\sum_{t=0}^{t_{END}} \frac{O\&M_t}{(1+r)^t}}{\sum_{t=0}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} = \frac{O\&M \cdot \sum_{t=0}^{t_{END}} \frac{1}{(1+r)^t}}{P \cdot 8760 \cdot Lf \sum_{t=0}^{t_{END}} \frac{1}{(1+r)^t}} = \frac{O\&M}{P \cdot 8760 \cdot Lf} \tag{23}$$

$$LUOM = \frac{(O\&M)_{FIX}}{8760 \cdot Lf} + (O\&M)_{VAR} \tag{24}$$

The term $(O\&M)_{FIX}$ is the annual fixed O&M cost expressed in terms of $ per kW(e) of installed capacity, and $(O\&M)_{VAR}$ is the variable O&M cost in terms of mills per kW·h of electricity produced; both values are input data for NEST.

The levelized cost of the nuclear fuel, including both front end and back end LUFC (mills/kW·h), was defined in Eq. (11). In the NEST basic model it is split into three terms:

$$LUFC = \frac{FC_1}{\eta \cdot \delta \cdot Lh} + \frac{FC_{RE}}{Q \cdot \eta} + \frac{SF}{Q \cdot \eta} \tag{25}$$

The term η (%/100) is the net thermal efficiency of the plant, δ (kW/kg HM) is the average power density in the reactor core at full power (during the first reactor cycle), *Q* (MW(d)/kg) is the average burnup of unloaded fuel, *SF* ($/kg HM) is the fuel back end cost of the type of reactor considered; all four values are input data to NEST. *Lh* is an intermediate parameter defined in NEST by Eq. (22).

The terms FC_1 and FC_{RE} are the levelized fuel front end costs per kg of heavy metal for the first core and the reload core, respectively. FC_1 is treated separately from FC_{RE} to provide the possibility of considering differences, e.g. in enrichment, between the first core and regular reload fuel. To define FC_1 and FC_{RE} , all stages of the front end of the fuel cycle have to be taken into account, as shown in Eq. (26):

$$FC = \sum_{k=1}^{Nstages} \left(SC_k \cdot SN_k \cdot HM_k \cdot \frac{1}{(1+r)^{t_k - t_0}} \right) \tag{26}$$

To define these parameters one has to know the corresponding data on heavy metal mass flow. N_{stages} is the *number* of stages at the front end of the fuel cycle, $N_{stages} = 4$; $k = 1$ is the stage with purchase of natural uranium, $k = 2$ is the stage of conversion, $k = 3$ is enrichment, and $k = 4$ is fuel fabrication. The term SC_k is the cost of a specific unit of service (e.g. for $k = 1$ it is U_{nat} purchase cost ($/kg), for $k = 3$ it is enrichment cost ($/SWU) at a specific stage of the front end of the fuel cycle, SN_k is the amount of the specific unit of service at any stage of the front end of the fuel cycle[8], $t_k - t_0$ is the time necessary to process fuel on the every stage of the front end starting from stage k onwards; all these values are input data to NEST.

The term HM_k is the quantity of heavy metal necessary at stage k to produce 1 kg of the final nuclear fuel taking into account all losses.

$$HM_k = \prod_{j=k}^{Nstages} HMI_j^{j+1} \cdot \left(1 + l_j\right) \tag{27}$$

HMI_j^{j+1} is the quantity of the heavy metal necessary at the stage 'j' to produce 1 kg of the fuel on the next stage '$j+1$' without accounting for the losses (i.e. in 'ideal' case); l_j are the losses of the uranium during processing on every stage of the front end (e.g. $j = 2$ losses at U conversion); all values are input data to NEST.

The term SN_3 stands for separative work units SWUs (see Eq. (26)) at the specific stage of uranium enrichment. The term SN_3 (SWU) is calculated using the following equation:

$$\begin{aligned} SN_3 &= (2\varepsilon_P - 1)\cdot \ln\left(\frac{\varepsilon_P}{1-\varepsilon_P}\right) - (2\varepsilon_T - 1)\cdot \ln\left(\frac{\varepsilon_T}{1-\varepsilon_T}\right) \\ &- \frac{\varepsilon_P - \varepsilon_T}{\varepsilon_F - \varepsilon_T}\cdot\left((2\varepsilon_F - 1)\cdot \ln\left(\frac{\varepsilon_F}{1-\varepsilon_F}\right) - (2\varepsilon_T - 1)\cdot \ln\left(\frac{\varepsilon_T}{1-\varepsilon_T}\right)\right) \end{aligned} \tag{28}$$

ε_P is defined for the first core and for the reload fuel differently, namely, ε_{P1} for the fuel batch with the lowest enrichment in the first core fuel, ε_{P2} for the fuel batch with the middle enrichment in the first core fuel, and ε_{P3} for the fuel batch with the highest enrichment in the first core fuel and for the regular reload fuel. The term ε_F is the concentration of ^{235}U in natural uranium, and ε_T is the concentration of ^{235}U in the tails of the uranium enrichment plant. All values, namely, ε_{P1}, ε_{P2}, ε_{P3}, ε_F and ε_T are input data to NEST.

II.3.2. Calculation of LUEC for an alternative power plant

Equations (12), (20) and (22) used for calculation of LUEC, LUAC and Lh for an NPP can also be applied for a fossil power plant. Equation (21) for the IDC of a fossil fuel power plant may be simplified because in this case one uses generally a constant cash flow approximation with:

$$\omega_j = \frac{1}{T_C}$$

which gives:

$$IDC = ONT \cdot \left(\frac{1}{T_C} \sum_{t=t_{START}}^{0} \frac{1}{(1+r)^t} - 1\right) \tag{29}$$

For fossil fuel power plants, one usually assumes zero back fitting and decommissioning costs ($LUAC_{BF}$ and $LUAC_D$). Regular (planned) replacements of main equipment parts can be included in O&M costs.

Equation (23) for LUOM of an NPP can also be used for alternative power plants. The equation for LUFC (fuel costs) for fossil plants is significantly different compared with that for an NPP. It can be derived from Eq. (11). An important feature of thermal power plants is their heavy dependence on the fuel cost, which may escalate rapidly. Assuming that fuel costs can be approximated by equation $F_t = F_0 \cdot (1+i)^t$, where i is an escalation rate

($i = \frac{F_t}{F_{t-1}} - 1$)

[8] SN_k is used in case the costs SC_k of a specific fuel cycle stage (k = 1 to 4) are not directly available in the right dimension. In such a case, the value CN_k multiplied by SN_k should result in the correct dimension, e.g. for k = 1 in $/kg.

F_0 is the price of fuel to be spent per year at $t = 0$,

$$F_0 = 8760 \cdot P \cdot Lf \cdot \frac{3600 \cdot FS}{\eta},$$

and FS is a specific price of fuel at $t = 0$ in \$/GJ, we may transform Eq. (11) as follows:

$$LUFC = \frac{F_0}{P \cdot 8760 \cdot Lf} \cdot \frac{\sum_{t=0}^{t_{END}} \left(\frac{1+i}{1+r} \right)^t}{\sum_{t=0}^{t_{END}} \frac{1}{(1+r)^t}} = \frac{3600 \cdot FS}{\eta} \cdot \frac{\sum_{t=0}^{t_{END}} \left(\frac{1+i}{1+r} \right)^t}{\sum_{t=0}^{t_{END}} \frac{1}{(1+r)^t}} \tag{30}$$

Here, 3600 is a conversion factor from joules into watt-hours, and the rest of the parameters are defined above (see Eqs (23) and (25)).

All values in Eq. (30), namely η, FS, i, r, t_{START} and t_{END}, are input data to NEST.

The alternative power plant, which is originally represented above as a fossil fuel power plant, can be converted into any other energy source through the input of appropriate data. Applying this approach for a calculation of variable energy sources (e.g. wind, photovoltaic, etc.) the NEST user has to make sure that he takes into account the costs for a backup energy source in a correct manner since the current version of NEST does not do that automatically.

II.3.3. Calculation of IRR

To calculate the IRR *(%/100)*, NEST finds a solution for Eq. (19) within a range $0.005 \le r \le 0.5$. The IRR is calculated the same way for an NPP and a fossil fuel power plant.

II.3.4. Calculation of ROI

The ROI (1/a) is frequently derived as the 'return' (incremental gain) from an activity divided by the cost of that activity (by 'total overnight cost'). This parameter is calculated without discounting:

$$ROI = \frac{PUES - OM - FU}{ONT} \cdot 8760 \cdot Lf \tag{31}$$

ONT is the total overnight capital cost introduced in Eq. (20), and Lf is the load factor of the plant. PUES and these two values are input data.

OM is non-discounted O&M cost which is assumed to be distributed evenly during the plant lifetime, hence *OM* coincides with *LUOM* which is calculated using Eq. (24).

FU is defined by the following non-discounted formulas, which are derived from Eqs (25) and (26) at $r = 0$.

$$FU = \frac{FC_1}{8760 \cdot \eta \cdot \delta \cdot Lf \cdot t_{END}} + \frac{FC_{RE}}{Q \cdot \eta} + \frac{SF}{Q \cdot \eta} \tag{32}$$

$$FC = \sum_{k=1}^{Nstages} \left(SC_k \cdot SN_k \cdot HM_k \right) \tag{33}$$

The values in Eqs (32) and (33) are input data to NEST, and have been discussed for Eqs (25) and (26) above.

In the case of a fossil fuel power plant, the calculation of fuel costs *FU* which was demonstrated in Eq. (30) is simplified, as shown in the following.

$$FU = \frac{3600 \cdot FS}{\eta \cdot t_{END}} \cdot \sum_{t=0}^{t_{END}} (1+i)^t \tag{34}$$

All values in Eq. (34) are input data to NEST and are discussed for Eq. (30) above.

II.3.5. Calculation of NPV

The NPV is the levelized profit of an investment into a power plant and was defined in Eq. (14). NEST calculates the NPV using Eq. (16).

II.3.6. Calculation of total investment

Total investment INV (millions of dollars) means the investment needed for a plant up to commissioning, including usually capital overnight cost and interest during construction. We suppose that overnight cost includes contingency and owner costs:

$$INV = (ONT + IDC) \cdot P \tag{35}$$

The maximum investment INL a private utility planning to install a new plant could reasonably raise while maintaining its financial health could be defined in a simplified way as follows:

$$INL = M \cdot Sh \cdot PM \cdot t_{GR} \cdot \alpha \tag{36}$$

where *M* (million dollars/year) is the total market income of the electricity sector in a given country, *Sh* (%/100) is the market share of the private utility, and *PM* (%/100) is the profit margin of the tentative plant owner. The term t_{GR} (years) could be defined in two different ways: It is either the necessary payback time or it is the time the utility has available to accumulate profits before it has — depending on the growth of electricity consumption — to install a new plant or replace an old one. The parameter α is an adjusting coefficient (can be used by the assessor to account for special local conditions) normally equal to 1 and its other values are to be substantiated if necessary. *M*, *Sh* and t_{GR} are the results of energy planning activities which are a necessary prerequisite to an INPRO assessment and can be obtained normally from the authorities in a country.

II.3.7. Options available for version 1 of NEST

There are several options available for NEST version 1.

Depreciation tax benefit

Depreciation tax benefit is a type of 'hidden investment' applied by the governments to various sectors of the economy, including power generation. In the basic version of NEST, the possibility for such a tax benefit may either be ignored (as selected in Ref. [1]) or by choosing this option may be taken into account according to the Modified Accelerated Cost Recovery System MACRS [40] introduced by the Internal Revenue Service in the USA.

In this case, using Eq. (20) for the levelized capital costs of an NPP, LUAC (mills/kW·h), the calculation will be transformed as follows:

$$LUAC = \frac{ONT\left(1 - tax \cdot \sum_{t=1}^{16} \frac{DN_t}{(1+r)^t}\right) + IDC}{Lh} + \left(LUAC_{BF} + LUAC_D\right) \cdot (1 - tax) \tag{37}$$

DN_t (%/100) is the MACRS [40] coefficients for the NPP ($1 \le t \le 16$), and *tax (%/100)* is the tax rate. Both are input data for NEST.

The equation for the levelized capital costs of a fossil power plant (FPP) looks similar:

$$LUAC = \frac{ONT\left(1 - tax \cdot \sum_{t=1}^{21} \frac{DF_t}{(1+r)^t}\right) + IDC}{Lh} + \left(LUAC_{BF} + LUAC_D\right) \cdot (1 - tax) \tag{38}$$

DF_t *(%/100)* are the MACRS [40] coefficients for FPP (*1≤ t ≤21*).

The existing version of NEST allows users to define sets of depreciation coefficients other than those published in Ref. [40]. However, the total number of coefficients cannot exceed 16 for NPPs and 21 for FPPs. This restriction will be removed in the next editions of NEST.

Purchase of fresh fuel assemblies and 'take back' of spent fuel (i.e. a system with external fuel cycle).

The equations for the *LUEC* of a system with an external fuel cycle are identical to Eqs (20)–(24). Equation (25) for a fuel cost calculation will be modified as follows:

$$LUFC = \frac{PB_1 + PB_2}{2 \cdot MB \cdot \eta \cdot \delta \cdot Lh} + \frac{\frac{PB_{RE}}{MB} \cdot \sum_{t=0}^{t_{END}} \frac{(1+ef)^t}{(1+r)^t} + SF \cdot \sum_{t=0}^{t_{END}} \frac{(1+es)^t}{(1+r)^t}}{24000 \cdot Q \cdot \eta \cdot \sum_{t=0}^{t_{END}} \frac{1}{(1+r)^t}} \tag{39}$$

The terms *r*, *η*, δ, *Q, Lh* and *SF* are defined in Eqs (1), (22) and (25). *MB* (*kg*) is the mass of heavy metal per fuel bundle; PB_1 ($) is the price per bundle of fuel of the lowest enrichment used for a first core load; PB_2 ($) is the price per bundle of fuel of the middle enrichment used in a first core load (it is assumed that a first core comprises three equal portions of fuel with different enrichment); PB_{RE} ($) is the price per bundle of fuel of the regular enrichment used in a first core load and for reloading; *ef* (%/100) is the escalation rate of the fresh fuel price; *sf* (%/100) is an escalation rate of the spent fuel management price. All these parameters are the input to NEST.

Calculation of the series of power plants.

Calculation of the levelized cost of electricity for a series of power plants of different types and commissioned at different times within a period of 40 years (maximum difference between the first and the last power plant startup dates) can be performed in NEST based on the ideas presented in Ref. [41]. The cost of electricity from a group of power plants *GL* (mills/kW·h) is defined by the following equation:

$$GL = \frac{\sum_j \sum_{t=0}^{40a} \frac{U(j,t) \cdot P(j) \cdot LUEC(j) \cdot Lh(j)}{\left(1+r_j\right)^t}}{\sum_j \sum_{t=0}^{40a} \frac{U(j,t) \cdot P(j) \cdot Lh(j)}{\left(1+r_j\right)^t}} \tag{40}$$

where *U(j,t)* is the amount of power units of type *j* introduced in the moment *t*; and r_j is a discount rate for a particular type of power plant. *LUEC*, *Lh*, and *P* are defined in Eqs (8), (22) and (23). Summing is made with a step of 0.1 annum; up to 400 power plants can be introduced simultaneously. All parameters used in this equation are to be calculated in advance for every particular reactor type and recorded in the output areas of the spreadsheet used.

This option is not available in combination with the option of purchase of fresh fuel assemblies and 'take back' of spent fuel (i.e. a system with external fuel cycle).

The existing NEST edition performs only a cost calculation for a series of reactors. Calculation of other financial figures of merit (IRR, ROI, etc.) for a series of reactors will be available in the next editions of NEST.

Investment schedule

In a basic version of NEST one can use either integer or non-integer numbers in any combinations to introduce the investment schedule. Upon the request of NEST users, a special option was introduced for those who use only integer numbers defining the instants of investments portions. The investment can be done either at the beginning of the year specified by the user (as selected in Ref. [1]), or by choosing this option in the middle of the year according to an internationally agreed procedure.

Contingency cost schedule

Upon the request of the tool users, a special option was introduced for contingency cost accounting. The contingency costs may be distributed proportionally to the overnight cost distribution during the total construction period (as selected in Ref. [1]), or by choosing this option are taken into account at the end of the construction period, i.e. at the moment of reactor startup. In the second case, the interest during construction will not be accruing on the contingency.

II.3.8. Output of the basic version 1 of NEST

The main output of NEST consists of the value of:

— LUEC (mills/kW·h);
— IRR (%/100);
— ROI (%/100);
— NPV (millions of dollars);
— Total investment (millions of dollars) needed for installing a power plant — including its limit (millions of dollars) in the case of a private utility.

These values are presented in the basic version of NEST for two NPP types with an open uranium fuel cycle and for an alternative power plant which can be converted by the user into a fossil power plant, wind turbine, hydro plant or photovoltaic station by the introduction of suitable input data. The alternative power plant is labelled as FPP conditionally. The two types of NPPs are labelled in NEST as a PWR (e.g. LUEC (PWR), ROI (PWR), etc.) and an HWR, but could be any type of a thermal NPP with an open fuel cycle.

In addition to the main output presented above (for each version of NEST), there are several intermediate NEST results available on the Excel sheets. For instance, on the sheet called E1_LUEC_PWR, the user can find the value of LUAC (mills/kW·h) — the levelized capital costs (see Eq. (20), LUOM (mills/kW·h) — the levelized O&M cost (see Eq. (24), LUFC (mills/kW·h) — the levelized fuel cost (see Eq. (25), and IDC ($/kW(e)) — the interest accumulated during construction of the plant (see Eq. (21).

II.4. VERSION 2 OF NEST

The advanced version 2 of NEST is based on a model developed by Harvard University [2]. It investigates the economics of three different systems (Systems 1 to 3), consisting of a reactor with its associated fuel cycle:

System No. 1: A thermal NPP using low enriched uranium (LEU) as fresh fuel and direct disposal of spent fuel, i.e. it is a system with an open (once-through) fuel cycle.

System No. 2: A thermal NPP using LEU and MOX fuel based on the reprocessing of all spent fuel and multirecycling of plutonium and uranium. It includes the disposal of high level waste (HLW) from reprocessing spent LEU fuel and spent MOX fuel. That is, it is a thermal system with a partly closed fuel cycle.

System No. 3: A fast reactor using only MOX fuel and performing continuous plutonium and uranium recycling and disposal of HLW from reprocessing. That is, it is a system with a completely closed fuel cycle in equilibrium.

Together with the basic model of NEST, which was described in the previous section, i.e. NEST version 1, this model derived from a Harvard University study can be used for the three systems mentioned above to calculate the same economic parameters, i.e. LUEC, IRR, ROI, NPV and total investment.

II.4.1. System No. 1 of the model based on the Harvard University study

System No. 1 is a thermal NPP using LEU as fresh fuel and direct disposal of spent fuel, i.e. with an open (once-through) fuel cycle. This system is consistent with the nuclear systems of the basic model described in Section B.3. Nevertheless, the model based on the Harvard University study provides an alternative method of calculation, which is an interesting option to compare in some particular cases. The model for System No. 1 uses most of the input data of NEST version 1 (but not all), but also additional input as presented below.

Naturally, the general equations used in this model for calculating LUEC, IRR, ROI, NPV and total investment for System No. 1 are similar to the equations used in the basic version 1 of NEST. However, some specific values are calculated in a different manner.

Equation (12) of the basic model described above is valid for the LUEC definition in the model based on the Harvard University study. LUAC is defined in Eq. (41), LUOM in Eq. (48) and LUFC in Eq. (50):

Levelized unit life cycle amortization cost

$$LUAC = \frac{\left(C_{cap} + C_{cont}\right)\cdot\left(1+F_{idc}\right)\cdot\left(1+F_{preop}\right)}{8760\cdot Lf}\cdot\left(F_{cr}+F_{tax}+F_{ins}\right) \tag{41}$$

C_{cap} ($/kW·e) (the same parameter as OCC in version 1) is the total construction cost (overnight cost without contingency and 'other costs') normalized to the total electrical output of the plant; C_{cont} ($/kW·e) (the same parameter as CC in version 1) is the contingency cost to provide for costs overruns and other unforeseen costs; F_{preop} (%/100) is a factor that takes into account pre-operational costs, i.e. 'other costs before the plant begins full scale operation'; F_{tax} (%/100) is a factor defining the annual charges for property taxes; F_{ins} (%/100) is a factor defining the annual charges for insurance; Lf (%/100) is the average load factor of the plant, 8760 are the hours per year[9]. All factors are input to NEST.

F_{idc} and F_{cr} are defined by Eqs (42) and (43):

$$F_{idc} = \left[\sum_{t=t_{START}}^{0} \frac{f_t}{(1+r)^t}\right] - 1 \tag{42}$$

$$F_{cr} = \frac{1}{1-t_e}\cdot\left[\frac{(1-df)\cdot eir}{1-\frac{1}{(1+eir)^{t_{END}}}} + \frac{df\cdot dir}{1-\frac{1}{(1+dir)^{t_{END}}}} - \frac{t_e}{t_{END}} - df\cdot dir\cdot t_e\right] \tag{43}$$

F_{idc} is a factor considering interest during construction; the term f_t is the fraction of the total up-front costs borrowed at the beginning of year t modelled with a beta-binomial distribution (see below). The term r (%/100) is the real discount rate or weighted cost of capital.

F_{cr} is the fixed charge rate, i.e. the fraction of the initial investment that is collected each year to repay the principal investment (construction and other up-front cost) with a return of the investment. The term t_e is the income tax rate, t_{END} is the lifetime of the plant as it was introduced in Eq. (4); dir (1/year) is the debt interest rate, eir (1/year) is the equity interest rate and df (%/100) is the debt fraction. All parameters in Eq. (43) are input values to NEST.

[9] In the original Harvard University paper, a value of 8766 was used that takes into account the leap year, i.e. 8766 = 365 × 24 + 24/4.

The terms *ft* and *r* are defined in the following equations (bearing in mind that *t* and t_{START} are negative values here):

$$f_t = \frac{\Gamma(-t_{START})\Gamma(\alpha - t - 1)\Gamma(\beta + t - t_{START})\Gamma(\alpha + \beta)}{\Gamma(-t)\Gamma(t + 1 - t_{START})\Gamma(\alpha + \beta - t_{START} - 1)\Gamma(\alpha)\Gamma(\beta)} \quad (44)$$

$$\alpha = 1 + \exp\left[0.432 \cdot (t_{START} + 11.5)\right] \quad (45)$$

$$\beta = \frac{\alpha \cdot (1 - p)}{p} \quad (46)$$

$$r = df \cdot dir + (1 - df) \cdot eir \quad (47)$$

The terms α and β are intermediate dimensionless parameters that define the time distribution (shape) of investments. The parameter p is the dimensionless median value of investments, i.e. the fraction of the construction time at which half of the total capital investments has been spent. All these parameters are input values to NEST.

The levelized unit life cycle O&M cost *LUOM* (mills/kW·h) is defined in Eq. (48). In this model the O&M costs are represented in a form of fixed costs only, i.e. variable O&M costs, which were defined in Eq. (24), are merged with the fixed part. Decommissioning costs in this model are included in the O&M cost, unlike the basic model where decommissioning costs consist of capital costs.

$$LUOM = \frac{C_{om} + C_{dd} \cdot F_{dd}}{8760 \cdot Lf} \quad (48)$$

C_{om} ($/kW(e)/a) is the annual O&M cost $C_{om} = (O\,\&\,M)/P$, see Eq. (23); C_{dd} ($/kW€) is the decommissioning cost. These values are input to NEST. F_{dd} is the annual annuity factor and is defined in Eq. (49):

$$F_{dd} = \frac{i_{dd}}{(1 + i_{dd})^{t_{END}} - 1} \quad (49)$$

The term i_{dd} (1/a) is the annual rate of return on the funds invested in decommissioning, and are input to NEST.

The levelized unit fuel cycle cost *LUFC* (mills/kW·h) is defined in Eq. (50):

$$LUFC = \frac{\left[C_{leu} \cdot (1 + r)^{t_{leu}} + C_{is} \cdot (1 + r)^{-t_{is}} + C_{ds} \cdot (1 + r)^{-t_{ds}}\right] \cdot F_c}{24000 \cdot Q \cdot \eta} \quad (50)$$

The term t_{leu} (year) is the time from payment for fresh fuel till loading the fresh fuel into a reactor; t_{is} (year) is the time from fuel loading into a reactor until when spent fuel interim storage costs are to be paid; t_{ds} (year) is the time from fuel loading in a reactor till final disposal of spent fuel; C_{is} ($/kg HM) is the cost of the interim storage of spent fuel; C_{ds} ($/kg HM) is the cost of geological disposal of spent fuel; *Q* and η are defined in Eq. (25). 24 000 is the number of kilowatt-hours per megawatt-day. All terms are input to NEST.

$$F_c = \frac{t_{FU} \cdot r \cdot (1 + r)^{t_{FU}}}{(1 + r)^{t_{FU}} - 1} \quad (51)$$

F_c is the carrying charge factor. The term t_{FU} is the number of years that the nuclear fuel remains in a reactor, input to NEST.

C_{leu} is defined in the following Eq. (52):

$$C_{leu} = \frac{SC_4}{(1+r)^{-(t_4-t_0)}} + \frac{1}{1-l_4} \cdot \left[\frac{HM_3}{1-l_3} \cdot \left(\frac{SC_1}{(1-l_2)(1+r)^{-(t_1-t_0)}} + \frac{SC_2}{(1+r)^{-(t_2-t_0)}} \right) + \frac{SN_3 \cdot SC_3}{(1+r)^{-(t_3-t_0)}} \right] \quad (52)$$

C_{leu} (\$/kg HM) is the cost of fresh LEU fuel. The terms SC_k, l_k, t_k-t_0, and SN_k are defined in Eqs (26)–(28). All terms are input to NEST. HM_3 is defined in Eq. (53).

$$HM_3 = \frac{\varepsilon_P - \varepsilon_T}{\varepsilon_F - \varepsilon_T} \quad (53)$$

HM_3 (kg/kg) is the ratio of the amount used to feed natural uranium to one unit (e.g. kg) of enriched uranium (see Eq. (27)). The term ε_P is the concentration of U-235 in fresh fuel and is input to NEST; ε_F is the concentration of U-235 in natural uranium, i.e. $\varepsilon_F = 0.0071$. ε_T is defined in Eqs (54) and (55).

$$\varepsilon_T \approx 10^{-0.1631 \cdot (\log_{10} x)^2 + 0.47055 \cdot \log_{10} x - 2.6453} \quad (54)$$

$$x = \frac{(1-l_3) \cdot SC_3}{\frac{SC_1}{(1-l_2) \cdot (1+r)^{-(t_1-t_0)+(t_3-t_0)}} + \frac{SC_2}{(1+r)^{-(t_2-t_0)+(t_3-t_0)}}} \quad (55)$$

All terms in Eq. (55) are input to NEST and have been discussed above.

II.4.2. System No. 2 of the model based on the Harvard University study

System No. 2 is a thermal NPP using LEU and MOX fuel based on reprocessing of all spent fuel, multi-recycling of plutonium, reenrichment and multi-recycling of uranium retrieved from spent fuel and disposal of HLW from reprocessing, i.e. it is a thermal system with a partly closed fuel cycle.

As stated above, the model uses for System No. 2 most of the input data of NEST version 1 (but not all), but also additional input data as presented below.

Equations for the LUEC of System No. 2 — a thermal reactor with recycling of plutonium to produce MOX fuel — are identical to System No. 1 (see Eqs (41)–(49)), with the exception of the levelized unit fuel costs LUFC (mills/kW·h).

$$LUFC = \frac{\left[C_{leu} \cdot (1+r)^{t_{leu}} + C_{is} \cdot (1+r)^{-t_{is}} + C_{rr} \right] \cdot F_c}{24000 \cdot Q \cdot \eta} \quad (56)$$

All terms in Eq. (56) have already been discussed for Eq. (50) with the exception of C_{rr} *(*\$/kg HM*)*, which is the net present cost of reprocessing 1 kg of spent fuel.

$$C_{rr} = \frac{C_r}{(1+r)^{t_{repr}}} + \frac{C_{dh}}{(1+r)^{t_{hlw}}} - \frac{M_{Pu} \cdot C_{Pu}}{(1+r)^{t_{Pu}}} - \frac{M_U \cdot C_{rU}}{(1+r)^{t_{rU}}} \quad (57)$$

The term C_r *(*\$/kg HM*)* is the cost of reprocessing; C_{dh}*(*\$/kg HM*)* is the cost of final disposal of HLW; t_{repr} (years) is the time before reprocessing; t_{hlw} is the time before disposal of HLW; t_{Pu} is the time to get reprocessed plutonium; t_{rU} is the time to get reprocessed uranium. All these terms are input to NEST. M_{Pu}, M_U, C_{Pu} and C_{rU} are defined in the following equations.

$$M_{Pu} = (1 - l_{rPu}) \times \left(xpu_{238} + xpu_{239} + xpu_{240} + xpu_{241} \cdot 2^{\frac{-t_{repr}}{14}} + xpu_{242} \right) \tag{58}$$

M_{Pu} (kg/kg) is the relative mass of recovered plutonium. The term l_{rPu} (%/100) is the plutonium loss during reprocessing; xpu_m is the isotope fraction in spent fuel (m = 238 for Pu-238, m = 239 for Pu-239, etc.); t_{repr} (years) is the time before reprocessing. All these terms are input to NEST.

$$M_U = (1 - l_{rU}) \cdot (xu_{235} + xu_{236} + xu_{238}) \tag{59}$$

M_U (kg/kg) is the relative mass of recovered uranium. The term l_{rU} (%/100) is the uranium loss during reprocessing; xu_m is the isotope fraction in spent LEU fuel (m = 235 for U-235, etc.). All terms are input to NEST.

$$C_{Pu} = (1 - l_m) \cdot \frac{C_{leu} - C_{mox}}{xpu} \tag{60}$$

C_{Pu} ($/kg HM) is the 'value' of reprocessed plutonium and C_{leu} ($/kg HM) is the cost of fresh LEU fuel (see Eq. (52)). The term l_m (%/100) is the plutonium loss during MOX fuel fabrication; xpu (%/100) is the total content of plutonium (and americium) in fresh MOX fuel. Both terms are input to NEST. C_{mox} is defined in Eq. (61).

$$C_{mox} = \frac{C_{mf}}{(1+r)^{t_f}} + \frac{1 - xpu}{1 - l_m} \cdot \frac{C_{dU}}{(1+r)^{t_{dU}}} \tag{61}$$

The term C_{mf} ($/kg HM) is the cost of fabrication of MOX fuel; C_{dU} ($/kg HM) is the cost of depleted uranium; t_f (years) is the time between purchasing of plutonium and MOX fuel fabrication; t_{dU} is the time to get depleted uranium. All terms are input to NEST.

$$C_{rU} = \frac{HM_3 \cdot SC_1}{F_{repr}} + \frac{(1-l_2)\cdot(1+r)^{-(t_1-t_0)}}{F_{repr}} \cdot \left\{ \frac{HM_3 \cdot SC_2 - F_{repr} \cdot C_{rc}}{(1+r)^{-(t_2-t_0)}} + (1-l_3) \cdot \left[\frac{SN_3 \cdot (SC_3 - C_{rs})}{(1+r)^{-(t_3-t_0)}} + \frac{(1-l_4)\cdot(SC_4 - C_{rlf})}{(1+r)^{-(t_4-t_0)}} \right] \right\} \tag{62}$$

The term C_{rlf} ($/kg HM) is the fabrication cost of fuel from reprocessed U. All other terms in this equation were discussed above with the exception of F_{repr} which is defined in Eq. (63):

$$F_{repr} = \frac{\dfrac{\varepsilon_P \cdot xu_{235}}{xu_{235} - 0.21 \cdot xu_{236}} - \varepsilon_T}{\dfrac{xu_{235}}{xu_{235} + xu_{236} + xu_{238}} - \varepsilon_T} \tag{63}$$

All the terms in this equation were discussed above.

II.4.3. System No. 3 of the model based on the Harvard University study

System No. 3 is a fast nuclear reactor operating in a closed U–Pu fuel cycle with breeding ratio close to 1, based on reprocessing of spent fuel from a reactor core, blankets and multi-recycling of plutonium and uranium, and disposal of HLW from reprocessing, i.e. it is a fast breeder system with an equilibrium closed fuel cycle.

As stated above, the model uses for System No. 3 most of the input data of NEST version 1 (though not all), but also additional input data as presented below.

Equations for the *LUEC* of System No. 3 — a fast reactor operating in a closed U–Pu fuel cycle — are identical to System No. 1 (see Eqs (41)–(49)) with the exception of the levelized unit fuel costs LUFC *(*mills/kW h*)*.

$$LUFC = \left(\frac{C_{fc}}{(1+r)^{-t_{fc}}} + \frac{C_{rc}}{(1+r)^{-t_{rc}}} + \frac{C_{dc}}{(1+r)^{-t_{dc}}} \right) \cdot \frac{M_c \cdot F_{cc}}{8760} + \left(\frac{C_{fb} + f_u \cdot C_u}{(1+r)^{-t_{fb}}} + \frac{C_{rb}}{(1+r)^{-t_{rb}}} + \frac{C_{db}}{(1+r)^{-t_{db}}} \right) \cdot \frac{M_b \cdot F_{cb}}{8760} \qquad (64)$$

where

$$F_{cc} = \frac{t_{FU} \cdot r \cdot (1+r)^{t_{FU}}}{(1+r)^{t_{FU}} - 1} \qquad (65)$$

is a carrying charge factor for the reactor core fuel (exactly like Eq. (51)), and

$$F_{cb} = \frac{t_{BL} \cdot r \cdot (1+r)^{t_{BL}}}{(1+r)^{t_{BL}} - 1} \qquad (66)$$

is a carrying charge factor for the reactor blanket fuel.

C_{fc} ($/kg HM) is the cost of fabrication of fuel for the reactor core; C_{rc} *(*$/kg HM) is the cost of reprocessing of fuel from the reactor core; C_{dc} ($/kg HM) is the cost of disposal of HLW from the core fuel reprocessing; C_{fb} ($/kg HM) is the cost of fabrication of fuel for the reactor blanket; C_u ($/kg HM) is the cost of depleted uranium; C_{rb} ($/kg HM) is the cost of reprocessing fuel from the reactor blanket; C_{db} ($/kg HM) is the cost of disposal of HLW from blanket reprocessing; f_u (%/100) is an annual fraction of the uranium to the feed blanket; M_c (kg HM/MW(e)·a) is an annual specific loading of the reactor core; M_b (kg HM/MW(e)·a) is an annual specific loading of the blanket; t_{BL} (a) is the time for blanket fuel irradiation; t_{fc} (a) is the fabrication time of the reactor core fuel; t_{rc} (a) is the reprocessing time of the reactor core fuel; t_{dc} (a) is the time of disposal of HLW from reactor core reprocessing; t_{fb} (a) is the fabrication time of the blanket elements; t_{rb} (a) is the reprocessing time of the blanket; t_{db} (a) is the time of disposal of HLW from blanket reprocessing. All terms are input to NEST; t_{FU} was defined in Eq. (51).

II.4.4. Calculation of IRR, NPV, total investment and ROI

To calculate the IRR *(*%/100*)*, NEST can be used to find a solution for Eq. (19) within a range $0.005 \le r \le 0.5$. The *IRR* is calculated the same way for every NPP option.

The NPV was defined in Eq. (14). NEST can be used to calculate the NPV using Eq. (16) for every system described in Sections B.4.1 to B.4.3.

Total investment INV (millions of dollars) and the maximum investment INL a private utility planning to install a new plant could reasonably raise are calculated using the same equations as in the basic version approach described in Eqs (35) and (36).

Return on investment *ROI* (*1/a*) is calculated without discounting.

$$ROI = \frac{PUES - OM - FU}{\left(C_{cap} + C_{cont}\right) \cdot \left(1 + F_{preop}\right)} \cdot 8760 \cdot Lf \qquad (67)$$

C_{cap}, C_{cont} and F_{preop} are introduced in Eq. (41), and *Lf* is the load factor of the plant. *PUES* and these four values are input data.

OM is the non-discounted O&M cost which in this model includes a decommissioning cost.

$$OM = \frac{C_{om} + C_{dd}}{8760 \cdot Lf} \tag{68}$$

All input parameters are defined in Eq. (48).

FU depends on the system of the model based on the Harvard University study to be applied. For System No. 1 (the once-through fuel cycle) it is defined by the non-discounted Eq. (69), which is derived from Eqs (50) and (52).

$$FU = \frac{\left(C_{is} + C_{ds} + SC_4 + \frac{1}{1-l_4} \cdot \left[\frac{HM_3}{1-l_3} \cdot \left(\frac{SC_1}{(1-l_2)} + SC_2\right) + SN_3 \cdot SC_3\right]\right)}{24000 \cdot Q \cdot \eta} \tag{69}$$

All input parameters are defined in Eqs (50) and (52).

For System No. 2 (MOX), *FU* is defined by the non-discounted Eq. (70) which is derived from Eqs (56) and (57).

$$\begin{aligned} FU = {} & \frac{1}{24000 \cdot Q \cdot \eta} \cdot \Big(C_{is} + C_r + C_{dh} - M_{Pu} \cdot C_{Pu} - M_U \cdot C_{rU} + \\ & + SC_4 + \frac{1}{1-l_4} \cdot \left[\frac{HM_3}{1-l_3} \cdot \left(\frac{SC_1}{(1-l_2)} + SC_2\right) + SN_3 \cdot SC_3\right]\Big) \end{aligned} \tag{70}$$

All input parameters are defined in Eqs (56) to (63).

For System No. 3 (fast reactor in equilibrium), *FU* is defined by the following non-discounted Eq. (71), which is derived from Eq. (64).

$$LUFC = \left(C_{fc} + C_{rc} + C_{dc}\right) \cdot \frac{M_c}{8760} + \left(C_{fb} + f_u \cdot C_u + C_{rb} + C_{db}\right) \cdot \frac{M_b}{8760} \tag{71}$$

All input parameters are defined in Eq. (64).

II.4.5. Options available for version 2 of NEST and its output

There are several options available for NEST version 2:

- — Investment schedule, as it is described in Section B.3.7;
- — Contingency cost schedule, as it is described in Section B.3.7;
- — Depreciation tax benefit, as it is described in Section B.3.7;
- — Calculation of series of reactors, as it is described in Section B.3.7.

The output of version 2 of NEST consists of the value of:

- — LUEC (mills/kW·h);
- — IRR (%/100);
- — ROI (%/100);
- — NPV (millions of dollars);
- — Total investment (million of dollars) needed for installing a power plant — including its limit (millions of dollars) in the case of a private utility.

Version 2 of NEST covers only NPPs (does not cover alternative energy sources).

II.5. VERSION 3 OF NEST

The advanced version 3 of NEST is based on models developed by MIT [3]. It can be used for four additional cases (called Systems No. 1 to 4), consisting of a reactor with its associated fuel cycle:

System No. 1. An NPP using LEU as fresh fuel and direct disposal of spent fuel, i.e. it is a system with an open (once-through) fuel cycle. Fuel cycle services are not considered in this system. Fuel cost is introduced as a single item.

System No. 2. A system with an open (once-through) fuel cycle similar to System 1 with one exception. This system includes a fuel cycle services cost consideration.

System No. 3. An NPP using LEU and MOX fuel based on reprocessing of LEU spent fuel, mono-recycling of plutonium, and disposal of spent MOX fuel and of HLW from reprocessing spent LEU fuel, i.e. it is a thermal system with a partly closed fuel cycle.

System No. 4. An alternative power plant (fossil power plant which can be converted into hydro, wind, photovoltaic plant, etc. by the corresponding input data values).

The original approach demonstrated by MIT in Ref. [3] is a cash flow model which was adopted in NEST for the financial figures of merit calculation. Together with versions 1 and 2 of NEST, which were described in the previous sections, the NEST model based on the MIT study can be used for the four systems mentioned above to calculate the same economic parameters, i.e. LUEC, IRR, ROI, NPV and total investment.

II.5.1. System No. 1 of the model based on the MIT study

System No. 1 is an NPP using LEU and without fuel cycle service cost calculations. This system is consistent with the nuclear systems of the basic model and the model based on the Harvard University study described in Sections B.3 and B.4. Nevertheless, the MIT model provides an alternative method of calculation. The MIT model for System No. 1 uses most of the input data of NEST version 1 (though not all), but also additional input as presented below.

The general equations used in the MIT model for calculating LUEC, IRR, ROI, NPV and total investment for System No. 1 are similar to the equations used in the basic version 1 of NEST. However, some specific values are calculated in a different manner.

Equation (12) of the basic model described above is transformed for LUEC definition in the model based on the MIT study.

$$LUEC = LUAC + LUOMF \tag{72}$$

In this case, LUEC (mills/kW·h) includes two factors, the capital costs LUAC and the sum of O&M costs and the fuel costs LUOMF. The LUAC (mills/kW·h) is defined through Eq. (73):

$$LUAC = \frac{ONT}{Lh} \cdot \sum_{t=t_{START}}^{0} \frac{\omega_t \cdot (1+in)^t}{(1+r)^t} \tag{73}$$

ONT is the total overnight cost which was defined in Eq. (20); Lh is an intermediate parameter defined in Eq. (22); ω_t is the normalized distribution of funds over the construction period from t_{START} to *0* (negative values) introduced in Eq. (21); in (%/100) is an annual inflation rate. ω_t and *in* are the input data. *r* (%/100) is a nominal discount rate which is defined in the MIT model as follows:

$$rn = dir \cdot df + eir \cdot (1 - df) \tag{74}$$

where dir (%/100) is a debt interest rate, eir (%/100) is an equity interest rate and df (%/100) is a debt fraction (all three are input data). In practice, from the viewpoint of mathematics and the use of NEST, one can switch from nominal discount rates (rn) to the real discount rates (r) by assuming in = 0 in the model based on the MIT study.

Equation (74) makes two points. First, this model provides an opportunity to consider shares of investment (equity and debt). Second, the discount rate (nominal) is defined as a simple average of interests, which means that different payback periods for equity and debt cannot be analysed within this approach.

LUOMF (mills/kW·h) is defined as follows:

$$LUOMF = \frac{\sum_{t=1}^{t_{END}} Cfe_t + Cw_t + Comf_t + Comv_t + Cdec_t + Cinc_t}{Lh} \tag{75}$$

The discounted cost of nuclear fuel per year of NPP operation Cfe_t (\$/a), including inflation and escalation rates, is defined in Eq. (76):

$$Cfe_t = \frac{8760 \cdot Lf \cdot P \cdot Cfkg \cdot (1+rfe)^t \cdot (1+in)^t}{Q \cdot \eta \cdot (1+rn)^t} \tag{76}$$

where *rfe* (%/100) is the real annual fuel cost escalation rate, *Cfkg* (\$/kg HM) is the average cost of nuclear fuel per kg of HM (both are input data).

The discounted cost of HLW treatment per year of NPP operation Cw_t (\$/a) including inflation rate is defined in Eq. (77):

$$Cw_t = \frac{8760 \cdot Lf \cdot P \cdot W \cdot (1+in)^t}{(1+rn)^t} d \tag{77}$$

where *W* (mills/kW·h) is a nuclear waste fee (input data).

The discounted fixed part of annual O&M cost $Comf_t$ *(\$/a)*, including inflation and escalation rates, is demonstrated in Eq. (78):

$$Comf_t = P \cdot (O\&M)_{FIX} \cdot \frac{(1+rom)^t \cdot (1+in)^t}{(1+rn)^t} \tag{78}$$

where *rom* (%/100) is a real O&M cost escalation rate (input data).

The discounted variable part of the annual O&M cost $Comv_t$ *(\$/a)* including inflation and escalation is defined as following:

$$Comv_t = 8760 \cdot Lf \cdot P \cdot (O\&M)_{VAR} \cdot \frac{(1+rom)^t \cdot (1+in)^t}{(1+rn)^t} \tag{79}$$

The discounted annual fee of NPP decommissioning $Cdec_t$ ($/a) which is necessary to accumulate the funds needed to cover the decommissioning cost D (millions of dollars) is represented in Eq. (80):

$$Cdec_t = \frac{D}{t_{END} \cdot (1+rn)^t} \tag{80}$$

Incremental capital cost per year of operation $Cinc_t$ ($/a) inflated and discounted is defined in Eq. (81) as follows:

$$Cinc_t = ICC \cdot P \cdot \frac{(1+in)^t}{(1+rn)^t} \tag{81}$$

where ICC ($/kW(e)·a) is a specific incremental capital cost per year of operation (input data).

All other parameters used in Eqs (76)–(81) have been discussed above.

II.5.2. System No. 2 of the model based on the MIT study

System No. 2 is a once-through fuel cycle system which is similar to systems considered in previous sections and differs from the MIT System No. 1 in one detail. System No. 2 includes an NPP using LEU and a calculation of costs of the fuel cycle services.

The general equations used in System No. 2 of the model based on the MIT study for calculating *LUEC* repeat the equations used in System No. 1 and use most of the input data of System No. 1 (except fuel costs), but also additional input as presented below.

In addition to Eqs (72)–(81), System No. 2 defines an average cost of nuclear fuel per kg of HM *Cfkg* ($/kg HM), as demonstrated in Eq. (82). This parameter is used to calculate the discounted cost of nuclear fuel per year of NPP operation Cfe_t ($/a), which has been introduced in Eq. (76).

$$\begin{aligned} Cfkg = {} & SC_1 \cdot HM_3 \cdot \left(1+F_f \cdot \left((t_1-t_0)+\frac{t_{FU}}{2}\right)\right)+SC_2 \cdot HM_3 \cdot \left(1+F_f \cdot \left((t_2-t_0)+\frac{t_{FU}}{2}\right)\right)+ \\ & +SC_3 \cdot SN_3 \cdot \left(1+F_f \cdot \left((t_3-t_0)+\frac{t_{FU}}{2}\right)\right)+SC_4 \cdot \left(1+F_f \cdot \left((t_4-t_0)+\frac{t_{FU}}{2}\right)\right)+SF \cdot \left(1-F_f \cdot \frac{t_{FU}}{2}\right) \end{aligned} \tag{82}$$

The term F_f is a carrying charge factor for the fuel cycle services, defined in the MIT model as an input data (the NEST user can either evaluate it based on his/her experience or calculate it using Eq. (53)). All other parameters used in Eq. (82) are defined above (see Eqs (26), (51) and (53)).

II.5.3. System No. 3 of the model based on the MIT study

System No. 3 is a mono-recycling MOX fuel cycle system which is similar to the systems considered in Sections B.5.1 and B.5.2 and differs from them in fuel cycle cost calculation. It includes an NPP using LEU and MOX fuel and a calculation of costs of the front end and back end fuel cycle services, including reprocessing of Pu. Unlike the model based on the Harvard University study described in Section B.4, the model derived from the MIT study does not envisage recycling of U retrieved from LEU spent fuel.

The general equations used in System No. 3 of this model for calculating LUEC repeat the equations used in System No. 1, and it uses most of the input data of System No. 1 (except fuel cost), but also additional input as presented below.

In addition to Eqs (72) to (81), System No. 3 defines an average cost of nuclear fuel per kg of HM *Cfkg* ($/kg HM) as demonstrated in Eq. (83). This parameter is used to calculate the discounted cost of nuclear fuel per year of NPP operation Cfe_t ($/a) which has been introduced in Eq. (76).

$$Cfkg = \frac{xpu \cdot Cfu + spu \cdot Cfpu}{xpu + spu} \tag{83}$$

where *xpu* (%/100) is the total content of Pu and Am in fresh MOX fuel, and *spu* (%/100) is the total content of Pu in spent UOX fuel to be reprocessed. Both terms are input to NEST.

The cost of MOX fuel per kg of HM ($/kg) is calculated in Eq. (84):

$$\begin{aligned} Cfpu = {} & \frac{xpu}{spu} \cdot \left(C_r + C_{dh} - SF_D\right) \cdot \left(1 + F_f \cdot \frac{t_{FU}}{2}\right) + C_{mf} \cdot \left(1 + F_f \cdot \frac{t_{FU}}{2} \cdot \frac{xpu}{spu}\right) + \\ & + SF_D \cdot \left(1 - F_f \cdot \frac{t_{FU}}{2}\right) + \frac{xpu}{spu} \cdot F_f \cdot \left(tm_2 \cdot C_r + tw \cdot C_{dh} + tm_3 \cdot C_{mf} - tm_1 \cdot SF_D\right) \end{aligned} \tag{84}$$

The SF_D spent fuel storage and direct disposal cost (the cost of storage and direct disposal of MOX spent fuel is supposed to be equal to the cost of storage and disposal of LEU spent fuel).

C_r ($/kg) is a reprocessing cost and C_{dh} ($/kg) is an HLW storage and final disposal cost (both were discussed in Eq. (57)); C_{mf} ($/kg) is a MOX fabrication cost (discussed in Eq. (61)); tm_1 (a) is the time from the moment of UOX spent fuel purchase to MOX fuel loading into the reactor core; tm_2 (a) is the time from spent fuel reprocessing to MOX fuel load in a reactor core; tm_3 (a) is the time necessary for MOX fuel manufacturing; *tw* (a) is the time to get the waste form of HLW after spent fuel reprocessing. All terms are input to NEST.

The cost of LEU fuel per kg of HM *Cfu* ($/kg) in System No. 3 of the model based on the MIT study is calculated according to Eq. (82) demonstrated above.

II.5.4. System No. 4 of the model based on the MIT study

System No. 4 is an alternative power plant which was originally a fossil fuel power plant and can be converted into any other energy source through the input of appropriate data. Applying this system for a calculation of variable energy sources (e.g. wind, photovoltaic, etc.), the NEST user has to make sure that account is taken of the costs of a backup energy source since the existing version of NEST does not do that automatically.

Naturally, the general equations used in this model for calculating LUEC repeat some of the equations used in Systems 1–3, and it uses some of the input data of System No. 1, but also additional input as presented below.

In addition to Eqs (72)–(74), System No. 3 defines a levelized cost of operation, maintenance and fuel LUOMF (mills/kW·h), as demonstrated in Eq. (85). This parameter has been introduced in Eq. (72).

$$LUOMF = \frac{\sum_{t=1}^{t_{LIFE}} Cfe_t + Comf_t + Comv_t + Cdec_t + Cinc_t}{Lh} \tag{85}$$

where all parameters are discussed in Eq. (75) with the exception of Cfe_t ($/a), which is the discounted cost of fossil fuel per year of FPP operation including inflation and escalation rates:

$$Cfe_t = \frac{8760 \cdot 3412 \cdot 1.05506 \cdot Lf \cdot P \cdot Cf_{GJ} \cdot (1 + rfe)^t \cdot (1 + in)^t}{\eta \cdot (1 + rn)^t} \tag{86}$$

Cf_{GJ} ($/GJ) is the cost of fossil fuel per GJ of heat produced at combustion. All other parameters in Eq. (86) have been discussed above and are the input data for NEST calculations.

II.5.5. Calculation of IRR, NPV, total investment and ROI

The IRR *(%/100)* for the NEST model based on the MIT study can be calculated using Eq. (19) within a range of $0.005 \leq rn \leq 0.5$. The *IRR* is calculated identically for every NPP and alternative power plant option.

The *NPV* was defined in Eq. (14). NEST calculates the NPV using Eq. (16) for every system described in Sections B.5.1 to B.5.3.

Total investment INV (millions of dollars) and the maximum investment INL a private utility planning to install a new plant could reasonably raise are calculated using the same equations as in the basic version approach described in Section B.3.6, i.e. Eqs (35) and (36).

The ROI (1/a) is calculated without discounting.

$$ROI = \frac{\left(PUES - \frac{Cfkg}{Q \cdot \eta} + W + (O\,\&\,M)_{VAR}\right) \cdot 8760 \cdot Lf - \left((O\,\&\,M)_{FIX} + ICC + \frac{D}{P \cdot t_{END}}\right)}{ONT} \tag{87}$$

All parameters in this equation are the input data and have been discussed above (see Eqs (20), (31), (76)–(81)).

II.5.6. Options available for version 3 of NEST and its output

There are several options available for NEST, version 3:

— Investment schedule, as is described in Section B.3.7;
— Contingency cost schedule, as is described in Section B.3.7;
— Depreciation tax benefit, as is described in Section B.3.7;
— Calculation of series of reactors, as is described in Section B.3.7.

The output of version 3 of NEST consists of the value of:

— LUEC (mills/kW·h);
— IRR (%/100);
— ROI (%/100);
— NPV (millions of dollars);
— Total investment (millions of dollars) needed for installing a power plant, including its limit (millions of dollars) in the case of a private utility.

II.6. VERSION 4 OF NEST

NEST version 4 is the extension of the basic version 1 to the calculations of innovative fuel cycles, i.e. multi-recycling MOX and fast breeders. Version 4 of NEST uses for reactors the economic model of NEST version 1 [1], and for the fuel cycle the model of NEST version 2 (with a few modifications) originally developed by Harvard University [2]. It can be applied to calculate the same numerical economic parameters (LUEC, IRR, ROI, NPV and total investment) for three additional cases:

System No. 1 is a PWR that uses MOX fuel (multi-recycling of Pu and U).

System No. 2 is a fast breeder reactor with a closed fuel cycle in equilibrium, i.e. producing approximately the same amount of Pu as consuming.

System No. 3 is a fast breeder reactor with a given breeding ratio and a closed fuel cycle.

II.6.1. System No. 1 of version 4

System No. 1 is a thermal NPP using LEU and MOX fuel based on reprocessing of all spent fuel, multi-recycling of plutonium, reenrichment and multi-recycling of uranium retrieved from spent fuel and disposal of HLW from reprocessing, i.e. it is a thermal system with a partly closed fuel cycle.

As stated above, the model of version 4 uses the general economic approach of basic version 1 (see Section B.3) and the method of calculation of the fuel cost of NEST version 2. NEST version 4 uses most of the input data of NEST version 1 (but not all) and the fuel cycle services input data of NEST version 2.

The equations for the LUEC of System No. 1 — a thermal reactor with recycling of Pu to produce MOX fuel — are identical to the equations of the basic version (Eqs (12), (20)–(24) above), with the exception of the LUFC *(*mills/kW·h*)*. The LUFC is defined in Eq. (88):

$$LUFC = \frac{FC_1}{\eta \cdot \delta \cdot Lh} + \frac{FC_{RE}}{Q \cdot \eta} + \frac{C_{rr}}{Q \cdot \eta} \tag{88}$$

The calculation of terms FC is demonstrated in Eqs (26)–(28); calculation of C_{rr} is demonstrated in Eqs (57)–(63). Here, a coefficient of 24 000, which is used to harmonize dimensions, is not demonstrated explicitly.

II.6.2. System No. 2 of version 4

System No. 2 is a fast nuclear reactor operating in a closed U–Pu fuel cycle with breeding ratio close to 1, based on reprocessing of spent fuel from a reactor core and blankets and multi-recycling of plutonium and uranium, and disposal of HLW from reprocessing, i.e. it is a fast breeder system with an equilibrium closed fuel cycle.

As stated above, the model of NEST version 4 uses the general economic approach of basic version 1 (see Section B.3) and the method of calculation of the fuel cost of NEST version 2. Version 4 uses most of the input data of NEST version 1 (but not all) and the fuel cycle services input data of NEST version 2.

The equations for the LUEC of System No. 2 — a fast reactor operating in equilibrium fuel cycle (i.e. BR~1) — are identical to the equations of the basic version (Eqs (12), (20)–(24)) with the exception of the LUFC (mills/kW·h).

The LUFC is calculated according to Eqs (64)–(66).

II.6.3. System No. 3 of version 4

System No. 3 is a fast nuclear reactor operating in a closed U–Pu fuel cycle with a given breeding ratio, based on the reprocessing of spent fuel from a reactor core and blankets and multi-recycling of plutonium and uranium, and disposal of HLW from reprocessing, i.e. it is a fast reactor system with Pu breeding.

As stated above, the model of version 4 uses the general economic approach of the basic version 1 (see Section B.3) and the method of calculation of the fuel cost of version 2 (model based on HU). NEST version 4 uses most of the input data of NEST version 1 (but not all) and the fuel cycle services input data of NEST version 2.

Equations for the LUEC of System No. 4 — a fast reactor with given breeding ratio — are identical to the equations of the basic version (Eqs (12), (20)–(24)) with the exception of the LUFC (mills/kW·h). LUFC is calculated according to Eq. (89):

$$LUFC = \frac{\gamma \cdot FR}{\eta \cdot \delta \cdot Lh} + \frac{FR}{Q \cdot \eta} + \frac{HLD}{Q \cdot \eta} \tag{89}$$

The terms Lh, Q, η and δ have been discussed above. The fast reactor first core power distribution may be kept flat by leaving gaps between fuel bundles in a core, i.e. some assemblies will not be loaded into the reactor and their 'cells' will be empty during reactor operation. γ (%/100) is the characteristic of the amount of fuel uploaded into the first reactor core to be calculated as follows:

$$\gamma = \frac{\gamma_3 - \gamma_2}{\gamma_1 - \gamma_2} \tag{90}$$

where γ_1 (kg) is the mass of the reactor core (without blanket), γ_2 (kg) is the mass of a single batch of fuel at regular reloading of a core (without blanket) and γ_3 (kg) is the mass of a first reactor core fuel (without blanket).

The discounted fuel costs per kg HM, FR ($/kg) is calculated according to Eq. (91):

$$FR = \frac{C_{Pu} \cdot x_{Pu} \cdot (1+l_f)(1+l_p)}{(1+r)^{t_{pp}-t_0}} + \frac{C_{DU} \cdot x_U \cdot (1+l_f)(1+l_u)}{(1+r)^{t_{up}-t_0}} + \frac{C_{FF} \cdot (1+l_f)}{(1+r)^{t_f-t_0}} \tag{91}$$

The value of Pu, C_{Pu} ($/kg), recovered from the reprocessed spent fuel (average for the core and blanket) is defined in Eq. (92):

$$C_{Pu} = \frac{C_R \cdot (1+r)^{t_{Pu}-t_R} - C_{DU} \cdot (1-f_R) \cdot x_{U238} \cdot (1+r)^{t_{Pu}-t_{RU}}}{(1-f_R) \cdot \left(x_{Pu\text{-}238} + x_{Pu\text{-}239} + x_{Pu\text{-}240} + x_{Pu\text{-}242} + x_{Pu\text{-}241} \cdot \exp(-\lambda_{Pu\text{-}241} \cdot t_R)\right)} \tag{92}$$

C_{FF} ($/kg) is the fuel fabrication cost; x_{Pu} (%/100) is the Pu concentration in fresh fuel; x_U (%/100) is the uranium concentration in fresh fuel; l_p (%/100) is the loss of the Pu during purchase; l_u (%/100) is the loss of uranium during purchasing (l_u equals l_1 in Eq. (27)); l_f (%/100) is the loss of the heavy metal during fuel fabrication (l_f equals l_4 in Eq. (27)); $t_{pp} - t_0$ (a) is the time from Pu purchase until fuel loading in the core; $t_{up} - t_0$ (a) is the time from depleted U purchase until fuel loading in the core; $t_f - t_0$ (a) is the time needed for fuel fabrication; t_R (a) is the time until reprocessing is paid after fuel discharge; t_{Pu} (a) is the time until Pu is recovered after fuel discharge; t_{RU} (a) is the time until U is recovered after fuel discharge; f_R (%/100) is the fraction of Pu or U that is not recovered during reprocessing; $x_{Pu,I}$ (%/100) are plutonium isotope concentrations in spent fuel; $x_{U\text{-}238}$ is the U-238 concentration in spent fuel; $\lambda_{Pu\text{-}241}$ (1/a) is the Pu-241 half-life (14 years).

All terms in Eqs (91) and (92), including the fuel fabrication cost and Pu concentration in fresh fuel, are the average values for the reactor core and blankets. All terms in Eq (92) are input data.

The HLW final disposal cost per 1 kg of spent fuel reprocessed, average for the core fuel and blankets fuel is defined as follows:

$$HLD = \frac{C_{dh}}{(1+r)^{t_{dh}}} \tag{93}$$

C_{dh} ($/kg) is the cost of geological disposal of HLW per 1 kg of spent fuel (average of blanket and core fuel) reprocessed at time t_{dh}, including transportation; t_{dh} (a) is the time when HLW disposal is paid after fuel discharge.

II.6.4. Calculation of IRR, NPV, total investment and ROI

To calculate the IRR (%/100), NEST can be used to solve Eq. (19) numerically within a range $0.005 \le r \le 0.5$. The IRR is calculated the same way for every NPP option.

The NPV was defined in Eq. (14). Using NEST, we can calculate the NPV using Eq. (16) for every system described in Sections B.6.1 to B.6.3.

Total investment INV (millions of dollars) and the maximum investment INL that a private utility planning to install a new plant could reasonably raise are calculated using the same equations as in the basic version approach described in Eqs (35) and (36).

The ROI (1/a) is calculated without discounting (i.e. at $r = 0$) using Eqs (24), (31) and (89)–(93).

II.6.5. Options available for version 4 of NEST and its output

There are several options available for NEST version 4:

- Investment schedule, as is described in Section B.3.7;
- Contingency cost schedule, as is described in Section B.3.7;
- Depreciation tax benefit, as is described in Section B3.7;
- Calculation of series of reactors, as is described in Section B.3.7.

The output of version 4 of NEST consists of the value of:

- LUEC (mills/kW·h);
- IRR (%/100);
- ROI (%/100);
- NPV (millions of dollars);
- Total investment (millions of dollars) needed for installing a power plant, including its limit (millions of dollars) in the case of a private utility.

Version 4 of NEST covers only NPPs and does not cover alternative energy sources.

Appendix III

SIMPLIFIED NUMERICAL EXAMPLE OF A NEST APPLICATION

This appendix presents a numerical example of a NEST application, consisting of a set of input data for the different versions (models) in NEST and the main output of NEST for these models, i.e. LUEC, IRR, ROI, NPV and total investment. The objective of this example is to demonstrate the validity of the different approaches (models) used in NEST through the compliance of results (output) received with different versions for a relatively simple and transparent case.

Input data compilation is a major problem in the economic analysis of NESs, not only because of the great uncertainty in the values of published parameters, but also because of the different meaning authors assume for the same parameters. Economic data of nuclear installations are not only technology dependent, but also country specific. Unfortunately, some of the economic values published lack the appropriate justification that would allow estimating the reliability of these data. Compilation of input data and discussion of its reliability are out of the scope of this appendix. For a more detailed discussion of input data collection problems, reference is made to Chapter 5 in Ref. [42]. An example of the analysis of input data can be found in the NESA study for Belarus [43]).

III.1. SET OF INPUT DATA FOR DIFFERENT NEST VERSIONS

The set of input data was chosen to be as similar as possible for each version in NEST in order to be able to study the impact of the equations on the output used in each version. Thus, this set of data is not a demonstration of a reference set of input data.

Input data used in this example are based on the experience collected in several INPRO studies. They have been refined to eliminate effects which are covered in one version of NEST and are not treated in another. These details can be extremely sensitive, e.g. the introduction into NEST version 2 of a 2.7 % real estate tax rate and a 2.7 % insurance fee (as was done in the original HU study [2]) yields more than a 50% increase in the electricity production cost. Since the other models (versions 1 and 3 of NEST) do not consider these effects, it is assumed that both the real estate tax rate and insurance fee are 0 in the input for the model based on the HU study (version 2).

The following types of power plants were analysed for several models in NEST: A PWR with an open (once-through) fuel cycle, a coal fired plant, and a fast breeder reactor with a closed fuel cycle. However, this example is not a comparison between nuclear and non-nuclear options, since such a comparison depends mainly on input data used, which are country specific.

The depreciation tax benefit has not been taken into account in this particular analysis, implying that the depreciation schedule is distributed uniformly within the period of the reactor’s lifetime.

The following information is presented:

- — Three sets of input data (Table 8) and the corresponding results (Table 11) of a calculation of economic parameters for a PWR reactor operating with a once-through fuel cycle achieved with three different versions of NEST (the basic version, the approach based on the HU study and the model derived from the MIT study, see Sections II.3–II.5 in Appendix II).
- — Two sets of input data (Table 9) and results of calculation (Table 12) of economic parameters for a fossil power plant (FPP achieved with 2 different versions of NEST (basic version and the model based on MIT approach, Section II.3 and II.5 in Appendix II).
- — One set of input data (Table 10) and the result of a calculation (Table 13) of economic parameters for a fast reactor operating with a closed fuel cycle (version 4, see Appendix II, Section II.6).

Table 8 presents a full list of input data necessary for calculation in versions 1 to 3 of NEST of the economic parameters of a PWR operating with a once-through fuel cycle.

TABLE 8. COST CHARACTERISTICS ASSUMED FOR THE PWR UNDER CONSIDERATION

Parameters		Units	Version 1	Version 2	Version 3
Net electric power		MW(e)	1000	1000	1000
Overnight cost		$/kW(e)	5000	5000	5000
Contingency cost		$/kW(e)	0	0	—
Owners cost		$/kW(e)	0	—	—
Decommissioning cost			1 mill/kWh	$1300/kWe	$\$500 \cdot 10^6$
Backfitting cost		mills/kW·h	0	—	—
Average load factor		%/100	0.9	0.9	0.9
Lifetime		a	60	60	60
Construction time		a	5	5	5
Normalized capital investments schedule (share per annum) during construction	0	%/100	0	—	0
	—1	%/100	0.2	—	0.2
	—2	%/100	0.2	—	0.2
	—3	%/100	0.2	—	0.2
	—4	%/100	0.2	—	0.2
	—5	%/100	0.2	—	0.2
	—6	%/100	0	—	0
Median value of investments		—	—	0.65	—
Real discount rate		%/100	0.07	—	—
Interest rate on debt		1/a	—	0.07	0.07
Interest rate on equity		1/a	—	0.07	0.07
Debt fraction		%/100	—	0.5	0.5
Tax rate		%/100	0	0	0
Inflation rate		1/a	—	—	0
Income tax rate		%/100	—	0	—
Other pre-operational expenses rate		%/100	—	0	—
Real estate tax rate		%/100	—	0	—
Insurance fee		%/100	—	0	—
Price per unit of electricity sold		mills/kW·h	80	80	80

TABLE 8. COST CHARACTERISTICS ASSUMED FOR THE PWR UNDER CONSIDERATION (cont.)

Parameters	Units	Version 1	Version 2	Version 3
Fixed O&M cost	\$/kW(e)	100	100	100
Variable O&M cost	mills/kW·h	0	—	0
O&M real escalation rate	%/100	—	—	0
Incremental capital cost	\$/kW(e)/a	—	—	0
Nuclear waste fee	mills/kW·h	—	—	0
Real fuel price annual escalation rate	1/a	—	—	0
Rate of return of investment into decommissioning	%/100	—	0.03	—
Nuclear fuel backend cost	\$/kg HM	1000	—	1000
Cost of intermediate storage of spent fuel	\$/kg HM	—	200	—
Cost of direct disposal of spent fuel	\$/kg HM	—	800	—
Spent nuclear fuel average burnup	MW·d/kg HM	50	50	50
Net thermal efficiency of the plant	%/100	0.33	0.33	0.33
Reactor first core average power density	kW/kg HM	28.89	—	—
Natural U purchase cost	\$/kg	70	70	70
U conversion cost	\$/kg	10	10	10
U enrichment cost	\$/SWU	150	150	150
Nuclear fuel fabrication cost	\$/kg	300	300	300
Time from U purchasing to fuel loading	a	—1.5	1.5	1.5
Time from U conversion to fuel loading	a	—1	1	1
Time from U enrichment to fuel loading	a	—0.75	0.75	0.75
Time from fuel fabrication to loading	a	—0.5	0.5	0.5
Time between fuel purchase and loading into reactor	a	—	0	—
Time between fuel loading into reactor and storage	a	—	8	—
Time between fuel loading into reactor and disposal	a	—	50	—
Time in reactor core	a	—	4	4
Losses at U purchasing	%/100	0		—
Losses at U conversion	%/100	0.005	0.005	—
Losses at U enrichment	%/100	0	0	—

TABLE 8. COST CHARACTERISTICS ASSUMED FOR THE PWR UNDER CONSIDERATION (cont.)

Parameters	Units	Version 1	Version 2	Version 3
Losses at fuel fabrication	%/100	0.01	0.01	—
First core lowest U-235 concentration	%/100	0.02	—	—
First core medium U-235 concentration	%/100	0.03	—	—
Refuelling fuel U-235 concentration	%/100	0.045	0.045	0.045
Natural U-235 concentration	%/100	0.0071	0.0071	0.00711
Enrichment tails U-235 concentration	%/100	0.0025	—	0.0025
Annual carrying charge factor	%/100	—	—	0.1

Note: In these three models the decommissioning cost is treated in a different manner. In version 1 it is represented as a fixed surcharge to the cost of electricity; in version 2 decommissioning cost is a fixed value per unit of installed capacity; in version 3 decommissioning cost is a fixed sum for entire project. For the purpose of this simplified example, all three values, i.e. 1 mills/kW·h, \$1300/kW(e), and \$500 × 10^6 are adjusted to ensure the same influence on the electricity cost.

Table 9 presents a full list of input parameters necessary for calculations using versions 1 and 3 (Sections II.3 and II.5 of Appendix II) of NEST of the economic parameters for a fossil power plant (FPP).

TABLE 9. COST CHARACTERISTICS ASSUMED FOR THE FPP (COAL) UNDER CONSIDERATION (cont.)

Parameters	Units	Version 1	Version 3
Net electric power	MW(e)	1000	1000
Overnight cost	\$/kW(e)	1200	1200
Contingency cost	\$/kW(e)	0	—
Owners cost	\$/kW(e)	0	—
Decommissioning cost		0	0
Backfitting cost	mills/kW·h	0	—
Average load factor	%/100	0.85	0.85
Lifetime	a	30	30
Construction time	a	4	4

TABLE 9. COST CHARACTERISTICS ASSUMED FOR THE FPP (COAL) UNDER CONSIDERATION (cont.)

Parameters		Units	Version 1	Version 3
Normalized capital investments schedule (share per annum) during construction	0	%/100	0	0
	−1	%/100	0.25	0.25
	−2	%/100	0.25	0.25
	−3	%/100	0.25	0.25
	−4	%/100	0.25	0.25
	−5	%/100	0	0
	−6	%/100	0	0
Real discount rate		%/100	0.07	—
Interest rate on debt		1/a	—	0.07
Interest rate on equity		1/a	—	0.07
Debt fraction		%/100	—	0.5
Tax rate		%/100	0	0
Inflation rate		1/a	—	0
Price per unit of electricity sold		mills/kW·h	80	80
Fixed O&M cost		$/kW(e)	20	20
Variable O&M cost		mills/kW·h	5	5
O&M real escalation rate		%/100	—	0
Incremental capital cost		$/kW(e)/a	—	0
Fuel price		$/GJ	6	6
Real fuel price annual escalation rate		1/a	0.01	0.01
Net thermal efficiency of the plant		%/100	0.33	0.33

Table 10 presents a list of input parameters necessary for calculations using Version 4 (Section II.6 in Appendix II) of NEST of the economic parameters for a fast breeder operating with a closed fuel cycle.

TABLE 10. COST CHARACTERISTICS ASSUMED FOR A FAST REACTOR OPERATING IN A CLOSED FUEL CYCLE WITH BREEDING

Parameters		Units	Version 4
Net electric power		MW(e)	1000
Overnight cost		\$/kW(e)	10 000
Contingency cost		\$/kW(e)	0
Owners cost		\$/kW(e)	0
Decommissioning cost			1 mills/kW·h
Backfitting cost		mills/kW·h	0
Average load factor		%/100	0.9
Lifetime		a	60
Construction time		a	5
	0	%/100	0
	−1	%/100	0.2
	−2	%/100	0.2
	−3	%/100	0.2
	−4	%/100	0.2
	−5	%/100	0.2
Normalized capital investments schedule (share per annum) during construction	−6	%/100	0
Real discount rate	%/100	0.07	
Tax rate	%/100	0	
Price per unit of electricity sold	mills/kW·h	150	
Fixed O&M cost	\$/kW(e)	200	
Variable O&M cost	mills/kW·h	0	
Spent nuclear fuel average burnup	MW·d/kg HM	100	
Net thermal efficiency of the plant	%/100	0.40	
Reactor first core average power density	kW/kg HM	85.0674	
Fuel fabrication cost (average per core and blankets)	\$/kg HM	1500	
Fuel reprocessing cost (average per core and blankets)	\$/kg HM	1000	
Disposal cost of HLW per kg of reprocessed core and blankets fuel (av.)	\$/kg HM	200	

TABLE 10. COST CHARACTERISTICS ASSUMED FOR A FAST REACTOR OPERATING IN A CLOSED FUEL CYCLE WITH BREEDING (cont.)

Parameters	Units	Version 4
Depleted U cost	$/kg HM	6
Time before reprocessing	a	5
Time before HLW disposal	a	5
Time to get reprocessed Pu	a	5
Time to get reprocessed U	a	5
Time of fuel fabrication (average for core and blankets)	a	0.5
Losses at U purchasing	%/100	0
Losses at fuel fabrication	%/100	0.005
Losses of Pu and U at reprocessing	%/100	0.005
Total content of Pu and Am in fresh MOX (average per core and blankets)	%/100	0.091 31
Total content of depleted U in fresh MOX (average per core and blankets)	%/100	0.908 69
Fraction of Pu-238 in spent fuel	%/100	3.15E-05
Fraction of Pu-239 in spent fuel	%/100	0.0687
Fraction of Pu-240 in spent fuel	%/100	0.024 66
Fraction of Pu-241 in spent fuel	%/100	0.004 297
Fraction of Pu-242 in spent fuel	%/100	0.001 431
Fraction of U-235 in spent fuel	%/100	0.001 654
Fraction of U-236 in spent fuel	%/100	0.0001 43
Fraction of U-238 in spent fuel	%/100	0.8711

III.2. OUTPUT OF NEST CALCULATIONS

Using the NEST models described in Appendix II, the following results have been obtained.

TABLE 11. RESULTS OF THE ECONOMIC CALCULATION FOR A PWR (NPP)

Parameter	Units	NPP		
		Version 1	Version 2	Version 3
LUEC	mills/kW·h	74.9	74.0	72.9
NPV (at PUES = 80 mills/kW·h)	$/kW(e)	607	718	839
IRR (at PUES = 80 mills/kW·h)	%/100	0.076	0.078	0.079
ROI (at PUES = 80 mills/kW·h)	%/100	0.093	0.090	0.091
Total investment	Billions of dollars	6.15	5.90	6.15

TABLE 12. RESULTS OF THE ECONOMIC CALCULATION FOR A FOSSIL POWER PLANT (FPP)

Parameter	Units	FPP	
		Version 1	Version 3
LUEC	mills/kW·h	75.3	71.0
NPV (at PUES = 80 mills/kW·h)	$/kW(e)	468	901
IRR (at PUES = 80 mills/kW·h)	%/100	0.101	0.138
ROI (at PUES = 80 mills/kW·h)	%/100	0.103	0.151
Total investment	Billions of dollars	1.43	1.43

TABLE 13. RESULTS OF THE ECONOMIC CALCULATION FOR A FAST REACTOR (FR)

Parameter	Units	FR, Version 4
LUEC	mills/kW·h	133.3
NPV (at PUES = 150 mills/kW·h)	$/kW(e)	1978
IRR (at PUES = 150 mills/kW·h)	%/100	0.080
ROI (at PUES = 150 mills/kW·h)	%/100	0.096
Total investment	Billions of dollars	12.31

III.2.1. Discussion of results of the numerical example

The results in Table 11 demonstrate a good convergence of financial figures of merit for a simplified model of a PWR operating in a once-through fuel cycle calculated with three different NEST versions (versions 1 to 3 of NEST in Appendix II). The difference (up to 38%) in the values of NPV among the three versions is based on the difference between PUES and LUEC (see Eq. (16) in Appendix II)

In the case of FPPs (Table 12), the difference between electricity costs (LUEC) calculated with version 1 (basic model) and version 3 (based on the MIT study) is slightly higher than for the PWR (shown in Table 11), but it still lies within about 6 %. The difference in the NPV values of the FPP is caused by the same reason as discussed for the PWR above: The difference between PUES and LUEC (see Eq. (16) in Appendix II) for the FPP (Table 12) calculated with version 3 (based on the MIT study) is almost double the difference between PUES and LUEC calculated with version 1 (basic model). The NPV calculated with the basic model is half of the one calculated with the model based on the MIT study. The deviations between other values (IRR, ROI) calculated with versions 1 and 3 are correlated with the discrepancies of NPV.

The ratio of the costs of electricity LUEC from a fast breeder (Table 13) and a PWR (Table 11), namely 1.8, is almost proportional to the ratio of overnight costs (Tables 8 and 10), namely 2.0, of the two reactors. This result confirms the general conclusion on the relatively low contribution of fuel cycle expenses to the production cost of nuclear electricity structure.

Appendix IV

ECONOMICS OF DEVELOPMENT

IV.1. ECONOMICS OF THE DEVELOPMENT CYCLE

The INPRO BP, UR and CR can be used as tools[10] to assist investors, be they governments or industry, to assess whether or not to invest in technology development, i.e. RD&D, or in technology use, i.e. deployment of an innovative NES. Thus, the decisions makers involved in deciding whether to invest in the RD&D to develop a given system or component, i.e. the technology developers, would be expected to require information to show that, once the NES is developed, the cost of the product provided by the NES, e.g. energy, will be competitive with that of alternatives at the future time when the NES is deployed.

Once a NES is sufficiently developed, a decision needs to be made whether or not to commit to its deployment. In most, if not all Member States, this will involve another set of investors since, simplistically, deployment can be thought of as a two step process — the offering of the NES in a given market by the technology developer and the acquisition of the technology by technology users. Technology users need confidence, at the time a decision is being made to commit a given NES that once the NES has been constructed, commissioned and brought into service (a process that will take several years), the NES will deliver its product at a competitive price and so enable the technology user to earn an adequate return.

In this context, it is well to consider briefly the various stages of development in bringing a NES to the point of large scale deployment (see Section 4.4.3 of Ref. [1], judgment on the maturity of NES). First, preliminary work is carried out to define a concept for a NES. Such work is often funded by national governments in Member States having significant nuclear power programmes, e.g. in national laboratories and/or in universities. One output of such work needs to be an assessment of the potential of the proposed NES to meet national and international requirements, as set out e.g. in the INPRO methodology BP, UR, and CR, augmented by specific additional requirements that the Member States may have or may develop. Such an assessment also needs to identify uncertainties and the potential impact of such uncertainties using, e.g. sensitivity analysis. So, the INPRO methodology BP, UR, and CR can be used to assist decision makers at a very preliminary stage in deciding whether or not to commit funds to invest in RD&D to advance the development of an innovative NES beyond the preliminary stage. The proponent of an innovative NES may seek funding and assistance to advance the development of the NES from a number of possible sources — government and/or industrial. In the early stages development, the project may well be funded internally, but at later stages internal funds may be supplemented or replaced by external funds.

While development times vary among industrial sectors, in general, the more innovative the development, the longer will be the development time and the greater will be the uncertainty concerning a successful outcome, i.e. the higher the risk of a successful development, including, in the early stages, the uncertainty in the actual cost of development (see Table 4.3 in Chapter 4 of Ref. [1], which summarizes the different levels of technology maturity for development and deployment).

Development times for nuclear technology can extend to tens of years. Thus, the more innovative the development, the greater the likelihood that government support, in one form or another, will be needed and will be sought. Since the development decision is a decision to invest in RD&D, the cost of the RD&D must be estimated and an argument must be made that there will be a suitable return on the RD&D investment. Figure 1 shows an example of the dependence of the payback time for invested RD&D into the development of a commercial sodium cooled fast reactor (SFR) on the amount of RD&D spent and the size of the fleet with fast reactors (see Section 9.7 of Ref. [19]) calculated with the program MESSAGE [4].

The figure demonstrates that the size of a reactor fleet with SFRs should reach at least 30 GW(e) (assuming an installation rate of 1 GW(e) per year). Otherwise the payback time for RD&D investment becomes too long, i.e. more than 40 years. If the necessary RD&D investment is $40 billion to develop the SFR and only a fleet of 10 GW(e) plants would be installed, the payback time would become more than a century.

For investment by industry, financial analyses will be required to demonstrate that there is expected to be a financial payback. The justification for government investment may be partly financial, but could be based largely

[10] In Ref. [44], a NES consisting of fast reactors with a closed fuel cycle was assessed using the INPRO methodology.

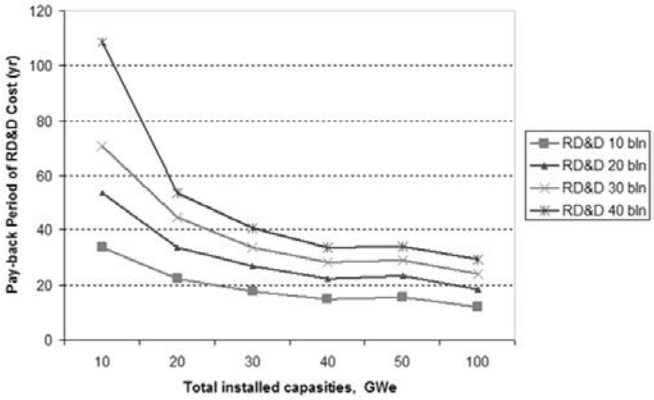


FIG. 1. Payback time for RD&D investment in a NES with sodium cooled fast reactors [19].

on the strategic benefits expected to be realized, e.g. maintenance and development of industrial capacity, security and diversity of energy supply, development and use of indigenous resources.

As development proceeds, periodic reassessments need to be carried out to confirm, with the improved knowledge base resulting from RD&D, that targets, and, in particular, the INPRO energy cost target, are still expected to be met and that future investments are justified. Throughout this process, close contact between the developer and potential users, i.e. the market(s), will impose a useful discipline to ensure that the needs of the users are understood and are being addressed.

At some stage, a commitment will be required to proceed with an FOAK plant. Prior to making such a decision, significant resources will have been committed to demonstrating key aspects/components of the NES, including possibly a prototype plant, and as these aspects/components are evaluated and demonstrated, the decision whether or not to commit funds for further development and demonstration would be based, in whole or in part, on a reassessment of whether the development targets, e.g. the INPRO BPs, URs and CRs, can still be achieved.

Where government funds have been used in development, the source of investment funds may well shift as a given innovative NES advances towards an FOAK plant, with an expectation that industry will accept a greater share of investment as uncertainty is reduced by RD&D. Thus, as the development process proceeds, the make-up of decision makers may well change. At the time of the commitment to an FOAK plant, the decision makers will almost certainly change since by definition the FOAK plant will be a ‘commercial’ plant, and so will involve investment by a technology user, i.e. a customer such as a utility. The investment to be made by the prospective technology user will have to be justified. Depending on the perceived risk, some form of government assistance or risk sharing between the technology developer and the first time technology user may still be required to convince the user to commit to the FOAK plant.

To illustrate, one can assume that committing to an FOAK plant would require a sharing of costs (for adaptation/completion of design, construction, commissioning, operation, etc.) and/or risk among the developer, the customer/utility and government. Each would need to be assured that its investment would provide a payback. Each would look at the issue from its own perspective. In all cases, the different decision makers/investors should have an expectation that once the plant is operating it will meet requirements such as INPRO’s BPs, URs and CRs. But each may evaluate the BPs, URs and CRs, somewhat differently, particularly those related to economics. Thus, for example, the government may take into account spin-off benefits, whereas a utility would be expected to consider the return on its investment, and the developer would need assurance that any additional investment required to complete the FOAK plant will be recovered (and ideally any sunk costs for RD&D already performed) from the sale and servicing of additional units.

Once an FOAK plant has been constructed, the decision makers/investors for future plants could well change again with the decision being much more a commercial decision between a customer and supplier resulting from a commercial negotiation. Governments may still be involved to a greater or lesser extent, e.g. in providing loan guarantees or, in the case of international sales, in assisting with financing. Again, the customers will want assurance that requirements will be met but, given the experience gained with the first plant, risks should be lower and so customer confidence should be higher. But the situation would be expected to be different depending on the customer’s nuclear experience and knowledge.

It may be noted that the costs of the construction of a standardized series of plants would be expected to lead to cost reductions as a result of learning. Learning will lead to savings in related areas, e.g. reductions in construction time and/or commissioning times. On the other hand, if there is a significant time span between projects, costs could increase as a result of so-called 'knowledge depreciation' (Section 4.1.2 in Ref. [45]).

If the customer is already an established user of nuclear technology, there may be a willingness to accept an innovative NES provided that a judgement has been made that the potential risk in doing so is offset by the benefits. On the other hand, if the customer for the innovative NES is a first time user of nuclear technology, the decision whether or not to acquire a given innovative NES may well be more complex, and in this case the nature of the offer may be very different than for a customer with relevant nuclear experience. Such a first time customer will probably be a late adopter of a given technology and would not be prepared to acquire an innovative NES (or component) until it has arrived at the stage of full commercial exploitation. Even then, the customer may well want the supplier to provide substantial support and technology transfer, even going so far as to want to contract for the O&M of the plant. But in the end, this customer must also be convinced that what is acquired will deliver a product that is competitive in the market, existing or anticipated, and that given the price structure in that market an appropriate return will be realized.

IV.2. RECOVERY OF DEVELOPMENT COSTS OF AN NPP

The question of whether or not to invest in developing an NPP and its associated fuel cycle is a complex one and, in many respects, is beyond the scope of the INPRO Manual. Nonetheless, a few general comments can be made about the use of an INPRO assessment in assisting with such decision making.

In this context, the INPRO methodology requirements related to the design can be considered to be economic performance goals that an NPP should meet. Thus, a technology development organization considering whether to initiate the development of an NPP, or to continue a development already under way, should carry out an assessment whenever a significant investment commitment is to be made. As development proceeds, periodic assessments would be carried out to determine if, once developed, the NPP and its fuel cycle would meet the INPRO methodology requirements in the area of economics. The economic assessor for an NPP under development would need the same basic information as required by an economic assessor looking into deployment of an NPP. But some aspects of the assessment would be somewhat different. It is these differences that are considered in this section.

It may be noted in setting specific development criteria that a judgment concerning the capacity to raise investments of a given amount for investment in a given region can be obtained from a review of the historical investments in that region, particularly those in energy supply. In the end, the investment in a NES must be affordable and attractive in a given investment climate, taking into account other investment options and other priorities requiring a share of available capital.

It should be clear from the proceeding discussion that coming to a decision on whether to invest in developing an NPP can be complex. The decision making can be simplified, somewhat, if the development organization can justify the development on the basis of a domestic requirement. In this case, the market and market conditions may be easier to define and to characterize, development costs may be supported in whole or in part by national governments, etc. But, even in these circumstances, an economic assessment would be expected to be performed to assess the economic competitiveness of the resulting product.

The decision making can also be simplified somewhat if the development is relatively straightforward, such as a modification to one component of a plant that has already been placed into commercial service, or an evolutionary design of a new NPP. In these cases the cost to carry out the development is relatively smaller.

Development of an innovative design of an NPP is a major undertaking and represents a significant risk to the technology developer. Because of this it is most likely that such developments would only be undertaken with the support of national governments. In the early stages of development, making the case to justify such an investment would be based, in the main, on strategic arguments rather than on detailed market assessments. But as development proceeds it would be expected that economic assessments related to deploying the NPP would become increasingly important and would be a major consideration when deciding to proceed with a prototype or FOAK plant.

Deciding how to recover this investment is not a simple matter. Basically, an argument needs to be developed setting out how many units can be expected to be sold into which markets, over which the investment would be recovered. The present value of the payback component of the price, i.e. the overnight cost to the customer, needs to be calculated using the developer's discount rate for comparison with the present value of the development investment, to determine whether the proposed investment in development is attractive to the developer, using its methods of evaluating investment opportunities. Thus, in estimating investment payback the assessor needs to also know the timing of cash flows from sales. Depending on the scope of supply that the developer foresees, the payback might be distributed over several cost components. The simplest approach would be to include the payback in the overnight capital cost to be quoted to future customers.

The process of determining cost recovery is iterative. An estimate of the number of sales and of their timing is developed using information from market assessments. Thus, before undertaking development, the technology development organization must understand the markets into which the NPP is to be deployed. A first estimate of the payback component of the cost of development, to be included in the price, is made and the NPV of this is calculated for comparison with the NPV of the investment needed for the development, to ensure that the investment can, in fact, be paid back. Once it is clear (for the assumed number of sales) that the payback component of the cost is sufficient to justify the investment, the payback component is included in the overnight cost and the LUEC, IRR, ROI, etc., are determined by the assessor as if the assessor was the customer of the NPP. To do so, the assessor now needs to use a representative discount rate or rates that would be used by prospective customers when they carry out their own assessments. Information on discount rates — that would be used by customers — needs to be provided by a marketing organization that is familiar with the markets into which the NPP is expected to be sold.

The values of LUEC, IRR, ROI, as well as the total investment cost to be incurred by the customer are then provided to the marketing organization, which has to make a judgment about whether they would be attractive to the customers that are expected to buy the NPP when it is developed. If so, the process is completed. If not, an adjustment has to be made and the process repeated. The adjustment could be to challenge the development team to make changes to the plant, for example, to reduce the overnight capital cost, or to reduce the scope of development and so reduce the development costs, and hence the payback component that needs to be charged to the customer, etc. One possible outcome is a decision not to proceed further with development.

In very well known nuclear initiatives [46], different scenarios and assumptions about nuclear competitors have been taken from referenced studies in order to calculate a competitive target for innovate nuclear plants. A number of studies dealing with the economics of future electricity supply have been published [47–49]. Such published scenarios are useful for an assessor using the INPRO methodology, as the reference values (usually time dependent), and detailed specific nuclear system costs, could be used to produce the data that are needed for the economic assessment. This is a typical approach used by developers/designers of new technologies because they are fully informed about the technical details of their nuclear power products, and they prefer to use data about competitive products taken from references. This approach could be easily used to collect input data for the economic assessment and the results would be consistent with the reference values if the deployment rate of the reactor type of interest could be considered to be a perturbation of the reference nuclear scenario (for example, for some specific region, or for a shorter time frame).

Comparing different options for development

In the discussion above, it has been assumed that the economic assessor is considering whether or not to invest in developing a specific design of an NPP. Another situation may arise where different nuclear technologies are competing for investment. In such a case, the economic assessor would determine the LUEC, IRR and ROI for the different options and compare them. The option that offered, once developed, the better economic performance would then be preferred. As discussed, the LUEC, IRR and ROI are calculated using a process that factors into the calculation of the costs of development. Thus, technologies that require less funding to develop, i.e. those that are at a more advanced stage of development, would, all other things being equal, have better economic financial performance. Hence, to justify the development of totally new systems requires a significant improvement in basic economic performance to ensure that including a relatively larger payback cost does not result in costs and financial figures of merit that are not competitive.

In an assessment of innovative designs at an early stage of development, all the technical data may not be available to perform a full cost calculation, as can be done for reactors already in operation and evolutionary designs that employ commercially mature components of an energy supply system. For example, just to calculate the French PWR fuel cycle costs for a comparative assessment using N4 fuel cycle data, approximately 150 input data are required, without taking into account taxes [50]. Thus, a calculation of economic parameters of an innovative NES may need to be done using a more simplified approach, based on fewer (but still up to 30 to 40) data for each power source (as presented in Refs [31, 32]). However, the data used need to be consistent with the chosen energy scenarios and alternatives. Experience shows that such simpler calculations for the nuclear fuel costs “are *broadly consistent with those of more detailed analysis”* [33].

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual — Economics, Volume 2 of the Final Report of Phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA-TECDOC-1575/Rev.1, IAEA, Vienna (2008).

[2] BUNN, M., et.al, The economics of reprocessing vs. direct disposal of spent nuclear fuel, Rep. DE-FG-26-99FT4028, Harvard University, Cambridge MA (2003).

[3] ANSOLOBEHERE, ST., et al, The Future Of Nuclear Power – An Interdisciplinary MIT Study, MIT, (2003).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Tools and Methodologies for Energy System Planning and Nuclear Energy System Assessment, Sustainable Energy for the 21st Century, IAEA, Vienna (2009).

[5] GENERATION IV INTERNATIONAL FORUM (GIF), Cost Estimating Guidelines for Generation IV Nuclear Energy Systems, Revision 4.2, Rep. GIF/EMWG/2007/004, OECD/NEA, Paris (2007).

[6] DEPARTMENT OF ENERGY, A Technology Roadmap for Generation IV Nuclear Energy Systems, DOE, Washington, DC (2002), www.inel.gov/initiatives/generation.shtml

[7] RASIN, H.P., et.al, User's Manual for G4-ECONS Version 2.0, A Generic EXCEL Based Model for Computation of the Projected Levelized Unit Electricity Cost (LUEC) and/or Levelized Non Electricity Unit Product Cost (LUPC) from Generation IV systems, Rep. GIF/EMWG/2008/002, OECD, Paris (2008).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Economic Evaluation of Bids for Nuclear Power Plants, 1999 Edition, Technical Reports Series No. 396, IAEA, Vienna (2000).

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Invitation and Evaluation of Bids for Nuclear Power Plants, IAEA Nuclear Energy Series No. NG-T-3.9, IAEA, Vienna (2011).

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Issues to Improve the Prospects of Financing Nuclear Power Plants, IAEA Nuclear Energy Series No. NG-T-4.1, IAEA, Vienna (2009).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, UNITED NATIONS DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS, INTERNATIONAL ENERGY AGENCY, EUROPEAN ENVIRONMENT AGENCY, Energy Indicators for Sustainable Development: Guidelines and Methodologies, IAEA, Vienna (2005).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual — Economics, Volume 2 of the Final Report of Phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA-TECDOC-1575/Rev.1, IAEA, Vienna (2008).

[13] ROGNER, H.H., LANGLOIS, L., Moving targets. Economic competitiveness of nuclear power, IAEA Bull. **42** 2 (2000) 36–42.

[14] TRAINER, T., Can solar sources meet Australia's electricity and liquid fuel demand? Int. J. Global Energy Issues **1** 1 (2003) 78.

[15] OMOTO, A., Improving economics of nuclear power — Towards safe, efficient and professional operation, The European Conference, Paris (2002).

[16] MEDLOCK III, K.B., HARTLEY, P., The Role of Nuclear Power in Enhancing Japan's Energy Security, The James A. Baker III Institute For Public Policy of Rice University, http://www.rice.edu/energy/publications/japanenergysecurity_nuclear.html, (2004).

[17] INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment of Nuclear Energy Systems based on a Closed Fuel Cycle with Fast Reactors (Joint Study), IAEA-TECDOC-1639/Rev.1, IAEA, Vienna (2012).

[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Energy Development in the 21st Century: Global Scenarios and Regional Trends, IAEA Nuclear Energy Series No. NP-T-1.8, IAEA, Vienna (2010).

[19] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability — Final Report of the INPRO Collaborative Project GAINS, IAEA Nuclear Energy Series NP-T-1.14, IAEA, Vienna (2013).

[20] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Special Report on Emission Scenarios (SRES), Cambridge University Press, Cambridge (2000).

[21] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons learned from Nuclear Energy System Assessments (NESA) using the INPRO Methodology, A Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA-TECDOC-1636, IAEA, Vienna (2009).

[22] INTERNTAIONAL ATOMIC ENERGY AGENCY, Economics of Nuclear Desalination: New Developments and Site Specific Studies, Final Results of a Coordinated Research Project 2002–2006, IAEA-TECDOC-1561, IAEA, Vienna (2007).

[23] INTERNATIONAL ATOMIC ENERGY AGENCY, Desalination Economic Evaluation Program (DEEP-3), User's Manual, Computer Manual Series No. 19, IAEA, Vienna (2006).

[24] INTERNATIONAL ATOMIC ENERGY AGENCY, web site of the IAEA Nuclear Energy programme, http://www.iaea.org/NuclearPower/NEA/index.html

[25] OECD/NUCLEAR ENERGY AGENCY, INTERNATIONAL ENERGY AGENCY, Projected Costs of Generating Electricity, OECD, Paris (1998).

[26] SESONKE, A., Nuclear Power Plant Design Analysis, Atomic Energy Commission, Washington, DC (1973).

[27] Gas Turbine World 1997, Handbook, for Project Planning, Design and Construction, Pequot Publishing, New York (1997), http://www.business-magazines.com/product.php?prd=176866&siteid=HomeBMS
[28] ATOMIC ENERGY COMMISSION, Guide for Economic Evaluation of Nuclear Reactor Plant Design, Rep. NUS-531, AEC, Washington, DC (1969).
[29] DELENE, J.G., HUDSON II, C.R., Cost Estimate Guidelines for Advanced Nuclear Power Technologies, Rep. ORNL/TM-10071/R3, Oak Ridge National Laboratory, Oak Ridge, TN (1993).
[30] UNION INTERNATIONALE DES PRODUCTEURS ET DISTRIBUTEURS D'ENERGIE ELECTRIQUE (UNIPEDE), General Report of the Group, Electricity Generating Cost, Evaluation Made in 1990 for Plant to be Commissioned in 2000, UNIPEDE, Paris (1991).
[31] OECD/NUCLEAR ENERGY AGENCY, INTERNATIONAL ENERGY AGENCY, Projected Costs of Generating Electricity, Update 1997, OECD, Paris (1998).
[32] UNION INTERNATIONALE DES PRODUCTEURS ET DISTRIBUTEURS D'ENERGIE ELECTRIQUE (UNIPEDE), Electricity Generating Cost for Thermal and Nuclear Plants to be Commissioned in 2005, UNIPEDE, Paris (1997), http://www.unipede.org
[33] OECD/NUCLEAR ENERGY AGENCY, INTERNATIONAL ENERGY AGENCY, Projected Costs of Generating Electricity, Update 1992, OECD, Paris (1993).
[34] INTERNATIONAL ATOMIC ENERGY AGENCY, Case Study of the Feasibility of Small and Medium Nuclear Power Plants in Egypt, IAEA-TECDOC-739, IAEA, Vienna (1994).
[35] INTERNATIONAL ATOMIC ENERGY AGENCY, Energy and Nuclear Power Planning Study for Armenia, IAEA-TECDOC-1404, IAEA, Vienna (2004).
[36] INTERNATIONAL ATOMIC ENERGY AGENCY, Comparative Studies of Energy Supply Options in Poland for 1997–2020, IAEA-TECDOC-1304, IAEA, Vienna (2002).
[37] INTERNATIONAL ATOMIC ENERGY AGENCY, Comparative Assessment of Energy Options and Strategies in Mexico until 2025, IAEA-TECDOC-1469, IAEA, Vienna (2005).
[38] INTERNATIONAL ATOMIC ENERGY AGENCY, Methodology for the Economic Evaluation of Cogeneration/Desalination Options, DEEP, A User's Manual, Computer Manual Series No. 12, IAEA, Vienna (1997).
[39] The Mathematics of MACRS Depreciation, http://www.milefoot.com/math/businessmath/topics/macrs.htm
[40] SHROPSHIRE, D., WILLIAMS, K., SMITH, J.D., BOORE. B., Advanced Fuel Cycle Economic Sensitivity Analysis, Rep. INL/EXT-06-11947, Idaho National Laboratory, Idaho Falls (2006).
[41] DE ROO, G., PARSONS, J.E., Nuclear Fuel Recycling: The Value of the Separated Transuranics and the Levelized Cost of Electricity, No. 09-008. Massachusets Institute of Technology, Cambridge, MA (2009), http://web.mit.edu/ceepr/www/publications/workingpapers/2009-008.pdf
[42] INTERNATIONAL ATOMIC ENERGY AGENCY, Role of Thorium to Supplement Fuel Cycles of Future Nuclear Energy Systems, IAEA Nuclear Energy Series No. NF-T-2.4, IAEA, Vienna (2012).
[43] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Assessment of the Planned Nuclear Energy System of Belarus, IAEA-TECDOC-1716, IAEA, Vienna (2013).
[44] INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment of Nuclear Energy Systems Based on a Closed Fuel Cycle with Fast Reactors, IAEA-TECDOC-1639/Rev.1, IAEA, Vienna (2012).
[45] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance on the Evaluation for Innovative Nuclear Reactors and Fuel Cycles, Report of Phase 1A of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA-TECDOC-1362, IAEA, Vienna (2003).
[46] STAHLKOPF, K.E., NOBLE, D.M., DEVINE, J.C., SUGNET, W.R., The United States Advanced Light Water Reactor (USALWR) Development Program, Trans. Am. Nucl. Soc. Suppl. 1, No. 56 (1988).
[47] LAKO, P., SEEBREGT, A.J., Characterization of Power Generation Options for the 21st Century, Report on Behalf of the Macro Task E1, Rep. ECN-C-98-085, Brussels (1998).
[48] NAKI11ĆENOVIĆ, N., GRÜBLER, A., McDONALD, A., Global Energy Perspectives, IIASA, WEC, Cambridge University Press, Cambridge (1998).
[49] DELENE, J.G., SHEFFIELD, J., WILLIAMS, K.A., REID, R.L., HADLEY, S., An Assessment of the Economics of Future Electric Power Generation Options and the Implications for Fusion, Rep. ORNL/TM-1999-243, Oak Ridge National Laboratory, Oak Ridge (1999).
[50] OECD/NUCLEAR ENERGY AGENCY, The Economics of the Nuclear Fuel Cycle, OECD, Paris (1994).

GLOSSARY

assessment. The assessment of a nuclear energy system is carried out at the criterion level of the INPRO methodology. In the case of a numerical criterion, the assessment process consists of a comparison of 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 carried out by answering the question raised. In principle, analyses using analytical tools are not part of an INPRO assessment but could provide the necessary input for an assessment. In the area of economics it is recommended that the assessor performs the calculation of indicators and acceptance limits using the simple methodology NEST developed within INPRO.

assessor. The assessor is an expert or a team of experts applying the INPRO methodology in a nuclear energy system assessment.

criterion (CR). Enables the INPRO assessor to determine whether and how well a user requirement is being met by a given nuclear energy system. A criterion consists of an indicator (IN) and an acceptance limit (AL). Indicators may be based on a single parameter, on an aggregate variable, or on a status statement. Acceptance limits could be international or national regulatory limits, or 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 evaluation parameters associated to simplify the assessment process.

discount rate (r). The parameter r takes the time value of money into account. It is used to levelize or discount expenditures and income of the operator during the lifetime of a plant to a defined point in time, usually the beginning of full power operation. It is also a measure of the risk of investment for installation of a new plant.

evaluation parameters (EP). These parameters were introduced to assist the INPRO assessor in determining whether a criterion has been met. In some cases these evaluation parameters have their own acceptance limits, in which case they could be called subindicators.

evolutionary design. An advanced design that achieves improvement over existing designs through small to moderate modifications, with a strong emphasis on maintaining proven design features to minimize technological risks. Examples of evolutionary reactors are the Generation III or Generation III+ reactors.

innovative design. An advanced design which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. Examples of innovative reactors are the Generation IV reactors.

innovative nuclear energy system. A system that encompasses all systems to be built after 2004 that will position nuclear energy to make a major contribution to global energy supply in the 21st century. In this context, such systems may include evolutionary as well as innovative designs of nuclear facilities.

INPRO Basic Principle (BP). A statement of a general goal that is to be achieved in a nuclear energy system to be sustainable in the long term and provides broad guidance for the necessary development (or a design feature thereof). The wording of a basic principle always utilizes the verb ‘shall’ or ‘must’.

internal rate of return (IRR). The discount rate that results in an NPV of 0. The higher the IRR, the higher is the attractiveness of the investment.

levelized unit energy cost (LUEC). The average price for the energy supplied that customers would have to pay during the operational lifetime of the plant to compensate for all the costs incurred by the owner/operator of the plant, taking the time value of money into account. LUEC is also the average price of energy sold during the lifetime of the plant for that NPV, i.e. the difference between total levelized income and expenditures, becomes 0. The lower the value of LUEC the higher is the competiveness of a plant.

net present value (NPV). The difference between the levelized (discounted) income and the expenditures accrued during the lifetime of a plant. The higher NPV the higher is the attractiveness of the investment.

return on investment (ROI). The total income minus the operation and maintenance and fuel cost, divided by the total expenditures accrued during the lifetime of the plant. It is not a discounted or levelized value. The higher the ROI the higher is the attractiveness of the investment.

user requirement (UR). Defines what should be done to meet the target/goal of the basic principle and 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. The wording of a user requirement utilizes the verb ‘should’.

ABBREVIATIONS

AGS	alternative generating source
AL	acceptance limit
BP	basic principle
CA	energy cost of alternative energy source
CN	energy cost of a nuclear energy system
CR	criterion
DU	depleted uranium
EMW	Geconomics and modelling working group within GIF
EP	evaluation parameter
EUR	European Utility Requirements
FOAK	first of a kind
FPP	non-nuclear (fossil fuel) power plant
FR	fast reactor
G4-ECON	Seconomic model of the EMWG
GC	IAEA General Conference
GIF	Generation IV International Forum
HLW	high level waste
HWR	heavy water reactor
I&C	instrumentation and control
IEA	International Energy Agency (OECD)
IDC	interest during construction
IIASA	International Institute for Applied System Analysis
IN	indicator
INSAG	International Nuclear Safety Group (IAEA)
IRR	internal rate of return
LDC	levelized discounted cost
LUAC	levelized unit life cycle amortization cost
LUEC	levelized unit energy cost
LUFC	levelized unit life cycle fuel cost
LUOM	levelized unit life cycle operation and maintenance cost
LWR	light water reactor
MACRS	modified accelerated cost recovery system
NES	nuclear energy system
NESA	nuclear energy system assessment
NPP	nuclear power plant
NPV	net present value
NOAK	Nth of a kind
O&M	operation and maintenance
ONT	total overnight capital cost including contingency and owners costs
PSA	probabilistic safety assessment
PUES	reference price for unit of electricity sold
PWR	pressurized water reactor
r	real discount rate
RD&D	research, development and demonstration
RES	resolution of the IAEA General Conference
ROI	return on investment
UR	user requirement

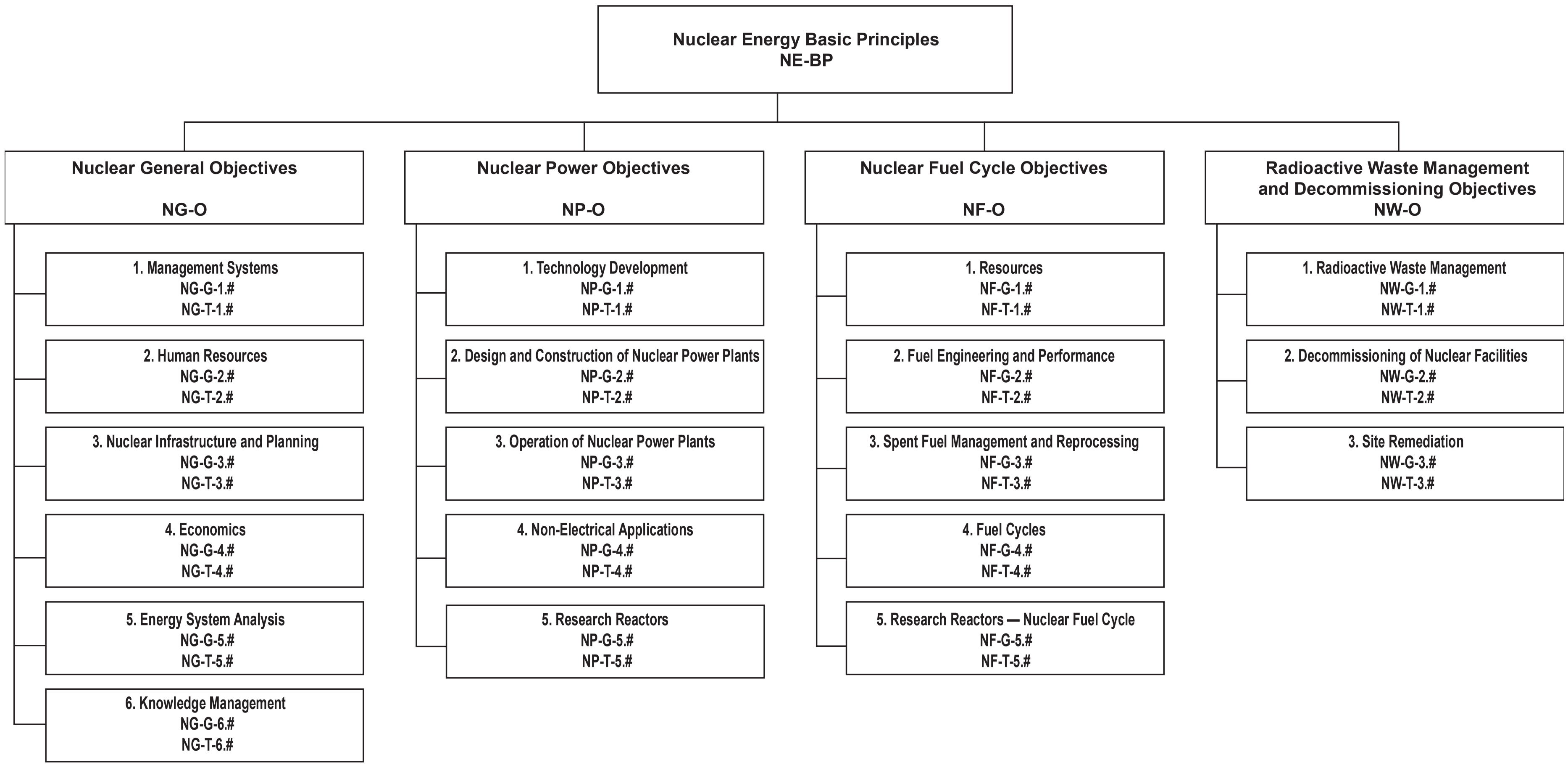
CONTRIBUTORS TO DRAFTING AND REVIEW

Allan, C.	Consultant, Canada
Depisch, F.	Consultant, Germany
Drace, Z.	International Atomic Energy Agency
Fesenko, G.	Consultant, Russian Federation
Korinny, A.	International Atomic Energy Agency
Maheshwari, N.K.	Bhaba Atomic Research Centre, India
Phillips, J.	International Atomic Energy Agency
Sato, K.	Japan Atomic Energy Agency, Japan
Shropshire, D.	International Atomic Energy Agency

Consultants Meeting

Vienna, Austria: 21–23 November 2012

Structure of the IAEA Nuclear Energy Series



Key

BP: Basic Principles
O: Objectives
G: Guides
T: Technical Reports
Nos 1-6: Topic designations
#: Guide or Report number (1, 2, 3, 4, etc.)

Examples

NG-G-3.1: Nuclear General (**NG**), Guide, Nuclear Infrastructure and Planning (topic **3**), **#1**
NP-T-5.4: Nuclear Power (**NP**), Report (**T**), Research Reactors (topic **5**), **#4**
NF-T-3.6: Nuclear Fuel (**NF**), Report (**T**), Spent Fuel Management and Reprocessing (topic **3**), **#6**
NW-G-1.1: Radioactive Waste Management and Decommissioning (**NW**), Guide, Radioactive Waste (topic **1**), **#1**

IAEA
International Atomic Energy Agency

No. 23

ORDERING LOCALLY

In the following countries, IAEA priced publications may be purchased from the sources listed below or from major local booksellers.

Orders for unpriced publications should be made directly to the IAEA. The contact details are given at the end of this list.

AUSTRALIA
DA Information Services
648 Whitehorse Road, Mitcham, VIC 3132, AUSTRALIA
Telephone: +61 3 9210 7777 • Fax: +61 3 9210 7788
Email: books@dadirect.com.au • Web site: http://www.dadirect.com.au

BELGIUM
Jean de Lannoy
Avenue du Roi 202, 1190 Brussels, BELGIUM
Telephone: +32 2 5384 308 • Fax: +32 2 5380 841
Email: jean.de.lannoy@euronet.be • Web site: http://www.jean-de-lannoy.be

CANADA
Renouf Publishing Co. Ltd.
5369 Canotek Road, Ottawa, ON K1J 9J3, CANADA
Telephone: +1 613 745 2665 • Fax: +1 643 745 7660
Email: order@renoufbooks.com • Web site: http://www.renoufbooks.com

Bernan Associates
4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4391, USA
Telephone: +1 800 865 3457 • Fax: +1 800 865 3450
Email: orders@bernan.com • Web site: http://www.bernan.com

CZECH REPUBLIC
Suweco CZ, spol. S.r.o.
Klecakova 347, 180 21 Prague 9, CZECH REPUBLIC
Telephone: +420 242 459 202 • Fax: +420 242 459 203
Email: nakup@suweco.cz • Web site: http://www.suweco.cz

FINLAND
Akateeminen Kirjakauppa
PO Box 128 (Keskuskatu 1), 00101 Helsinki, FINLAND
Telephone: +358 9 121 41 • Fax: +358 9 121 4450
Email: akatilaus@akateeminen.com • Web site: http://www.akateeminen.com

FRANCE
Form-Edit
5 rue Janssen, PO Box 25, 75921 Paris CEDEX, FRANCE
Telephone: +33 1 42 01 49 49 • Fax: +33 1 42 01 90 90
Email: fabien.boucard@formedit.fr • Web site: http://www.formedit.fr

Lavoisier SAS
14 rue de Provigny, 94236 Cachan CEDEX, FRANCE
Telephone: +33 1 47 40 67 00 • Fax: +33 1 47 40 67 02
Email: livres@lavoisier.fr • Web site: http://www.lavoisier.fr

L'Appel du livre
99 rue de Charonne, 75011 Paris, FRANCE
Telephone: +33 1 43 07 50 80 • Fax: +33 1 43 07 50 80
Email: livres@appeldulivre.fr • Web site: http://www.appeldulivre.fr

GERMANY
Goethe Buchhandlung Teubig GmbH
Schweitzer Fachinformationen
Willstätterstrasse 15, 40549 Düsseldorf, GERMANY
Telephone: +49 (0) 211 49 8740 • Fax: +49 (0) 211 49 87428
Email: s.dehaan@schweitzer-online.de • Web site: http://www.goethebuch.de

HUNGARY
Librotade Ltd., Book Import
PF 126, 1656 Budapest, HUNGARY
Telephone: +36 1 257 7777 • Fax: +36 1 257 7472
Email: books@librotade.hu • Web site: http://www.librotade.hu

INDIA
Allied Publishers
1st Floor, Dubash House, 15, J.N. Heredi Marg, Ballard Estate, Mumbai 400001, INDIA
Telephone: +91 22 2261 7926/27 • Fax: +91 22 2261 7928
Email: alliedpl@vsnl.com • Web site: http://www.alliedpublishers.com

Bookwell
3/79 Nirankari, Delhi 110009, INDIA
Telephone: +91 11 2760 1283/4536
Email: bkwell@nde.vsnl.net.in • Web site: http://www.bookwellindia.com

ITALY
Libreria Scientifica "AEIOU"
Via Vincenzo Maria Coronelli 6, 20146 Milan, ITALY
Telephone: +39 02 48 95 45 52 • Fax: +39 02 48 95 45 48
Email: info@libreriaaeiou.eu • Web site: http://www.libreriaaeiou.eu

JAPAN
Maruzen Co., Ltd.
1-9-18 Kaigan, Minato-ku, Tokyo 105-0022, JAPAN
Telephone: +81 3 6367 6047 • Fax: +81 3 6367 6160
Email: journal@maruzen.co.jp • Web site: http://maruzen.co.jp

NETHERLANDS
Martinus Nijhoff International
Koraalrood 50, Postbus 1853, 2700 CZ Zoetermeer, NETHERLANDS
Telephone: +31 793 684 400 • Fax: +31 793 615 698
Email: info@nijhoff.nl • Web site: http://www.nijhoff.nl

Swets Information Services Ltd.
PO Box 26, 2300 AA Leiden
Dellaertweg 9b, 2316 WZ Leiden, NETHERLANDS
Telephone: +31 88 4679 387 • Fax: +31 88 4679 388
Email: tbeysens@nl.swets.com • Web site: http://www.swets.com

SLOVENIA
Cankarjeva Zalozba dd
Kopitarjeva 2, 1515 Ljubljana, SLOVENIA
Telephone: +386 1 432 31 44 • Fax: +386 1 230 14 35
Email: import.books@cankarjeva-z.si • Web site: http://www.mladinska.com/cankarjeva_zalozba

SPAIN
Diaz de Santos, S.A.
Librerias Bookshop • Departamento de pedidos
Calle Albasanz 2, esquina Hermanos Garcia Noblejas 21, 28037 Madrid, SPAIN
Telephone: +34 917 43 48 90 • Fax: +34 917 43 4023
Email: compras@diazdesantos.es • Web site: http://www.diazdesantos.es

UNITED KINGDOM
The Stationery Office Ltd. (TSO)
PO Box 29, Norwich, Norfolk, NR3 1PD, UNITED KINGDOM
Telephone: +44 870 600 5552
Email (orders): books.orders@tso.co.uk • (enquiries): book.enquiries@tso.co.uk • Web site: http://www.tso.co.uk

UNITED STATES OF AMERICA
Bernan Associates
4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4391, USA
Telephone: +1 800 865 3457 • Fax: +1 800 865 3450
Email: orders@bernan.com • Web site: http://www.bernan.com

Renouf Publishing Co. Ltd.
812 Proctor Avenue, Ogdensburg, NY 13669, USA
Telephone: +1 888 551 7470 • Fax: +1 888 551 7471
Email: orders@renoufbooks.com • Web site: http://www.renoufbooks.com

United Nations
300 East 42nd Street, IN-919J, New York, NY 1001, USA
Telephone: +1 212 963 8302 • Fax: 1 212 963 3489
Email: publications@un.org • Web site: http://www.unp.un.org

Orders for both priced and unpriced publications may be addressed directly to:

IAEA Publishing Section, Marketing and Sales Unit, International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22488 • Fax: +43 1 2600 29302
Email: sales.publications@iaea.org • Web site: http://www.iaea.org/books

14-25901

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA
ISBN 978–92–0–102714–6
ISSN 1995–7807