Annals of Nuclear Energy 103 (2017) 122–129

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Benchmarking of nuclear economics tools

Megan Moore [a,*], Andriy Korinny [b], David Shropshire [b], Ramesh Sadhankar [a]

[a] Canadian Nuclear Laboratory, 286 Plant Rd, Chalk River, ON, Canada
[b] International Atomic Energy Agency, Vienna International Centre, PO Box 100, 1400 Vienna, Austria

ARTICLE INFO

Article history:
Received 24 October 2016
Received in revised form 12 January 2017
Accepted 17 January 2017

Keywords:
Nuclear economics
Levelised cost of energy
Generation IV reactors
Supercritical water reactors
Closed-fuel cycle economics
Fast reactors
NEST
G4ECONS

ABSTRACT

Benchmarking of the economics methodologies developed by the Generation IV International Forum (GIF) and the International Atomic Energy Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), was performed for three Generation IV nuclear energy systems. The Economic Modeling Working Group of GIF developed an Excel based spreadsheet package, G4ECONS (Generation 4 Excel-based Calculation Of Nuclear Systems), to calculate the total capital investment cost (TCIC) and the levelised unit energy cost (LUEC). G4ECONS is sufficiently generic in the sense that it can accept the types of projected input, performance and cost data that are expected to become available for Generation IV systems through various development phases and that it can model both open and closed fuel cycles. The Nuclear Energy System Assessment (NESA) Economic Support Tool (NEST) was developed to enable an economic analysis using the INPRO methodology to easily calculate outputs including the TCIC, LUEC and other financial figures of merit including internal rate of return, return of investment and net present value. NEST is also Excel based and can be used to evaluate nuclear reactor systems using the open fuel cycle, MOX (mixed oxide) fuel recycling and closed cycles.

A Super Critical Water-cooled Reactor system with an open fuel cycle and two Fast Reactor systems, one with a break-even fuel cycle and another with a burner fuel cycle, were selected for the benchmarking exercise. Published data on capital and operating costs were used for economics analyses using G4ECONS and NEST tools. Both G4ECONS and NEST predicted comparable TCIC and LUEC; with some variation in fuel cycle costs. The benchmarking exercise was also useful to understand the differences in the two methodologies for potential harmonisation opportunities in the future.

1. Background

Today's Generation III/III+ nuclear energy systems evolved through incremental technology changes to provide continuous improvements in the areas of: sustainability, safety and reliability, proliferation resistance and physical protection, and economics. Research into Generation IV nuclear energy systems marks a revolution in the industry, where novel ideas and new technologies are being considered with the hopes that significant improvements in safety, security, sustainability and economics of nuclear power can be realised. The economic assessment is an important aspect in the development of the Generation IV systems, from the concept development to the deployment phase, as the decisions on funding the various phases often depend on the expected economic benefits. To address this need both the International Atomic Energy Agency (IAEA), through the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), and the Generation IV International Forum (GIF), through the Economic Modeling Working Group (EMWG), developed economic analysis tools capable of assessing Generation IV reactors. Although both tools have been used for many economic assessments of Gen II, III and IV systems, this study marks the first attempt to benchmark the two tools. This benchmarking study was initiated by the EMWG,

Abbreviations: D&D, Decontamination and Decommissioning; DGR, Deep Geological Repository; EFPD, Effective Full Power Days; EMWG, Economic Modeling Working Group; FP, Fission Product; G4ECONS, Generation 4 Excel-based Calculation of Nuclear Systems; GIF, Generation IV International Forum; HPLWR, High Performance Light Water Reactor; IAEA, International Atomic Energy Agency; IDC, Interest During Construction; INPRO, IAEA Project on Innovative Nuclear Reactors and Fuel Cycles; IRR, Internal Rate of Return; kWe, Kilo-Watt Electric; LUAC, Levelised Unit Annual Capital Cost; LUDD, Levelised Unit Decontamination and Decommissioning Cost; LUEC, Levelised Unit Energy Cost; LUFC, Levelised Unit Fuel Cost; LUOM, Levelised Unit Operations and Maintenance Cost; MA, Minor Actinide; MIT, Massachusetts Institute of Technology; MOX, Mixed Oxide; MWe, Mega-Watt Electric; MWh, Mega-Watt Hour; NESA, Nuclear Energy System Assessment; NEST, NESA Economic Support Tool; NPV, Net Present Value; O&M, Operations and Maintenance; Pu, Plutonium; ROI, Return on Investment; TCIC, Total Capital Investment Cost; U, Uranium; UNF, Used Nuclear Fuel.

* Corresponding author.
E-mail address: megan.moore@cnl.ca (M. Moore).

http://dx.doi.org/10.1016/j.anucene.2017.01.020
0306-4549/

in collaboration with NEST tool developers at the IAEA, out of a desire to understand if the tools can be better aligned in an effort to provide consistent quality economic assessments of advanced nuclear energy systems to the interested parties. These exercises have been useful to understand the differences in the two methodologies for potential harmonisation opportunities in the future.

1.1. EMWG Generation 4 Excel-based Calculation of Nuclear Energy Systems (G4ECONS)

In 2000, nine countries formed the GIF (Generation IV International Forum, 2014). Today there are thirteen member countries: Argentina, Brazil, Canada, Euratom, France, Japan, the Republic of Korea, the Russian Federation, South Africa, Switzerland, the United Kingdom, and the United States (Generation IV International Forum, 2014). This forum endorsed six advanced nuclear energy systems for development through multi-lateral collaborations. GIF established specific goals related to sustainability, safety and reliability, proliferation resistance and physical protection, and economics (Generation IV International Forum, 2014) of the Generation IV systems. The economic goals are defined as follows:

1. The total financial risk of the advanced nuclear energy system should be comparable to other energy projects.
2. The advanced nuclear energy system should demonstrate a life cycle cost advantage over other energy sources exists.

The GIF EMWG was established with a goal to identify a methodology and toolkit flexible enough to support the economic analysis of a wide variety of reactor technologies at different stages of development and technical maturity (Economic Modeling Working Group, 2008). Upon review of the existing economic assessment methodologies, the EMWG chose to create the G4ECONS tool (Economic Modeling Working Group, G4-ECONS Model, 2008), supported by a comprehensive set of guidelines for estimating costs (Economic Modeling Working Group, 2007). The G4ECONS tool development was guided by four main requirements: simplicity, universality, transparency and adaptability (Economic Modeling Working Group, 2008). Therefore, the tool was made to be reasonably generic and has the ability to accept projected and actual input data, model open and closed fuel cycles, and is suitable for international use (i.e. the tool does not consider country specific taxation laws or economic practices). G4ECONS calculates two figures of merits, total capital investment cost (TCIC) and levelised unit energy cost (LUEC), to assess the Generation IV system against the two economic goals set by GIF.

The analysis in this report was completed using G4ECONS version 2.0.

1.2. NESA Economic Support Tools (NEST)

The IAEA assists Member States in capacity building related to long range and strategic planning for nuclear energy programmes in view of the long term commitment involved, with obligations that extend well beyond 100 years. INPRO project was initiated in 2000 to support sustainable development of nuclear energy systems. From 2001 to 2008, under the aegis of INPRO, the IAEA has developed a methodology for assessing the sustainability of nuclear energy systems. The INPRO methodology is structured around eight key issues that influence nuclear energy system sustainability, namely: economics, safety, proliferation, security, waste, environmental stressors, resources and infrastructure.

The NESA (Nuclear Energy System Assessment) Economic Support Tool (NEST) was developed to enable the INPRO assessment of the planned nuclear energy systems in the area of economics, and the scope of NEST calculations corresponds to the scope of INPRO methodology criteria in this area (International Atomic Energy Agency, 2014). NEST consists of a set of Excel spreadsheets that calculate parameters for different types of reactors, fuel cycles and for alternative systems (e.g. a fossil fuel power plant). NEST comprises the four modules[1] which are based on the different analytical models and can be used in parallel to estimate impact from specific methodological assumptions. The detailed description of the NEST modules is provided in International Atomic Energy Agency (2014) and can be briefly summarised as follows:

- Module v1 was developed within INPRO in 2004–2008 (International Atomic Energy Agency, 2008) and covers a nuclear power plant operating in once-through fuel cycle and alternative non-nuclear power plant
- Module v2 is based on Harvard University study (Bunn et al., 2003);
- Module v3 is based on a cash-flow model published by Massachusetts Institute of Technology (MIT) (Ansolabehere and et al., 2003);
- Module v4 is an extension of module v1 (involving some ideas of the module v2) designed for break-even closed fuel cycle system calculations and reactors operating with conversion rates other than one (breeders or burners).

Every module of NEST splits into two or three systems developed for calculation of specific systems (Table 1).

2. Cost estimating methodologies

2.1. Economics figures of merit

The benchmarking exercise is centred on the two figures of merit; namely, the TCIC and the LUEC calculated by the G4ECONS and NEST tools. In the GIF economic methodology, the TCIC formula in Eq. (1), is used to determine if the financial risk of the advanced nuclear energy system is comparable to other energy projects.

$$TCIC(\$/\text{kWe}) = \frac{Direct\ Costs + Indirect\ Costs + First\ Fuel\ Core(optional) + Interest\ During\ Construction}{net\ \text{kWe}\ installed} \quad (1)$$

[1] Historically NEST modules had been called ‘versions’ implying rather the versions of calculation results than the versions of a given tool. They always have been maintained and used in parallel as complementary modules (International Atomic Energy Agency, 2014).