Proceedings of the INMM & ESARDA Joint Annual Meeting
May 21-25, 2023

Economic Evaluation of Different Technologies for Electricity Generation Using INPRO Methodology

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ABSTRACT

An efficient, resilient, and capable energy supply is an important requisite for sustainable development. Nuclear energy can play an indispensable role in sustainable energy and support attaining carbon neutrality. The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), established in 2001, ensures nuclear energy is available to contribute to meeting the energy needs of the 21st century and beyond in a sustainable manner. INPRO integrates important aspects of nuclear energy sustainability in six topical areas: environment, safety, proliferation resistance, waste management, infrastructure, and economics. INPRO nuclear energy system assessment (NESA) helps identify gaps in sustainability in existing or planned nuclear energy systems. In the area of economics, INPRO developed the NESA economics support tool (NEST), which supports assessments in the economics area by calculating the levelized unit of energy cost (LUEC), return of investment (ROI), internal rate of return (IRR), and net present value (NPV). The NEST supports an analysis on economic competitiveness of innovative nuclear technology, with classic technologies based on fossil fuels, and renewable energy technologies with solar or wind for electricity generation. This economic analysis compared LUEC and other financial merits for six power plants using different technologies. The result shows that nuclear technology has a relatively lower LUEC and higher financial merits, especially for fast breeder reactors (FBR). The LUEC for solar and wind technologies is the highest, followed by the fossil fuel technology. The results confirmed the advantage of nuclear technology in the area of economics. This analysis aligns with other international studies, such as the United Nations Carbon Neutrality Project. This study is also useful for Member States in developing policy frameworks and long-term strategies for sustainable energy.

INTRODUCTION

Sustainable development is development that meets the needs of the present without compromising the ability of future generational to meet their own needs [1]. In the context of the United Nations Sustainable Development Goals (SDGs) and frameworks of sustainable development, particularly concerning climate change and environmental degradation, a clean, affordable, resilient, and reliable energy supply is an important requisite. Nuclear energy can play an indispensable role in sustainable energy and support attaining carbon neutrality [2,3]. In addition to the environmental contribution, the development of nuclear energy has a number of benefits across a range of social and economic indicators contributing to at least 10 of 17 SDGs, as shown in Figure 1.

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), established in 2001, ensures nuclear energy is available to contribute to meeting the energy needs of the 21st century and beyond in a sustainable manner. INPRO integrates important aspects of nuclear energy sustainability in six topical areas and develops a methodology for conducting a nuclear energy system assessment (NESA) in each area: environmental impacts (resource depletion and stressors) [4,5], safety (reactors and fuel cycle) [6, 7], proliferation resistance, waste management [8], infrastructure (including physical protection) [9], and economics [10]. The assessment is applied to evaluate a given nuclear energy system (NES) in a holistic manner to confirm its long-term sustainability or to identify issues or gaps that need to be addressed, as shown in Figure 2.

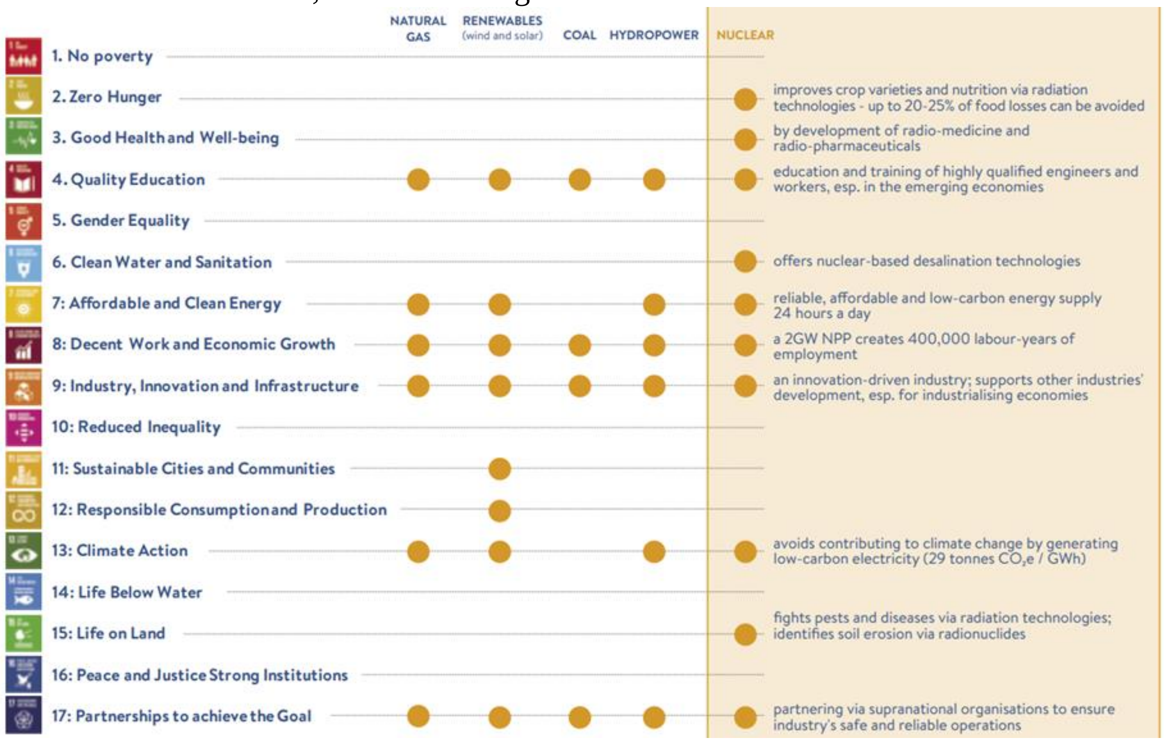

Figure 1. Nuclear technology contributions to achieving UN sustainable development goals (SDGs).

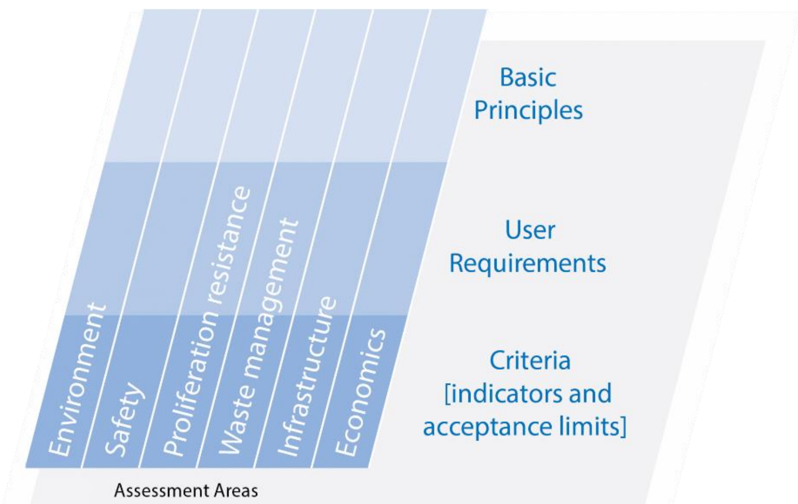

Figure 2. Diagram of the INPRO methodology showing the assessment areas.

The INPRO basic principle established for economics is "energy and related products and service from a nuclear energy system shall be affordable and available" [11]. Compared to other energy technologies for electricity generation, the cost of nuclear energy technology, taking all relevant costs and credits into account, should be competitive. Since nuclear power project is capital intensive and typically a large-scale project with a long gestation period and a long operating life, the affordability of its investment becomes more important, and a sound methodological approach is needed to conduct a comprehensive economic evaluation of nuclear energy system [11]. INPRO developed a set of tools which takes into account the key technical and economic characteristics of nuclear power reactors and can be used to conduct economic evaluation of other energy systems [12, 13, 14]. INPRO's economic evaluation of sustainability also provides assessment of the sustainability robustness of a nuclear materials management regime through the economics of various nuclear power scenarios, examining nuclear fuel purchases, use, storage, and handling of spent fuel (disposal or recycling).

1. Economics Evaluation

The economic evaluation covers seven different electricity generation options including a pressurized water reactor (PWR) with a once-through fuel cycle, a PWR with partly closed fuel cycle using mixed oxide (U-Pu) fuel (PWRmox), a heavy water reactor (HWR), a fast breeder reactors (FBR), a wind or solar-photovoltaic power plant (WSPP), and a fossil power plant or hydro power plant (FPP). There are different economic situations and stages of nuclear development amongst countries, therefore there would be significant uncertainties in an economic evaluation even for the same electricity generation options [11]. The six options chosen are predetermined according to general operational situations and the evaluations shown in this study are preliminary [11].

Cost accounting practices vary greatly from country to country, and there are different terminologies and definitions also used for categorization of various costs. The INPRO methodology used the accounting system developed by the IAEA for economic evaluations, which facilitated organizing all the costs related to a power project into various categories and ensured their completeness for use in nuclear energy technologies and for other types of energy technologies with some adjustments [11]. There are a range of methods used for calculating the cost of energy projects [12, 15], the most widely used is the levelized unit energy cost (LUEC) [11].

Levelized Unit Energy Cost (LUEC)

To build and operate a power system, a specific cash flow for building, fuelling, operating, and decommissioning the plant, including nuclear fuel and other nuclear waste management and refurbishment of facilities over their lifetime needs consideration. The levelized value of the expenditures $E(t_0)$ covers this cost and could be written using Eq. (1)[1]:

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

With: CI_t= Capital Investment expenditures at year t;
$O\&M_t$= Operation and maintenance (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 project (for a single unit consideration t_{END} is the lifetime of plant).

The levelized value of gross income GI (t_0) by selling electricity could be written using Eq. (2)[2]:

[1] The formula can be found in the NEST Algorithm Step 4 rev 1.0.
[2] The formula can be found in the NEST Algorithm Step 4 rev 1.0.

$$GI(t_0) = \sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^{t-t_0}} \cdot R_t \tag{2}$$

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

$\mathrm{R_t}$ = Electricity busbar price in year t (in a general case it is a time dependent value).

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 $E(t_0)$ — Eq. (1), is to be equalized to gross income $GI(t_0)$ — Eq. (2). There is an unlimited number of time dependent solutions R_t. Assuming that during the plant lifetime the cost of electricity R produced will be constant, one gets a single, unique constant cost of electricity R for a given discount rate r, defined by Eq. (3)[3]:

$$R = \frac{\sum_{t=t_{START}}^{t_{END}} \frac{CI_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} \tag{3}$$

The R in Eq. (3) 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. LUEC could be split into three main terms, capital/O&M/fuel[4]:

$$LUEC = \frac{\sum_{t=t_{START}}^{t_{END}} \frac{CI_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} + \frac{\sum_{t=t_{START}}^{t_{END}} \frac{O\&M_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} + \frac{\sum_{t=t_{START}}^{t_{END}} \frac{F_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} = LUAC + LUOM + LUFC \tag{4}$$

Where LUAC is the levelized unit life cycle amortization cost; LUOM is the levelized unit life cycle O&M cost, it can be grouped into fixed O&M cost and variable O&M cost; and LUFC is the levelized unit life cycle fuel cost. The method for calculating the fuel cost component of LUEC for a nuclear power plant is dependent on the technical considerations.

This economic method is embedded in INPRO tool NESA economics support tool (NEST) for economic evaluation of nuclear energy systems [11]. NEST is in a form that can be used to calculate parameters for different types of reactors with different fuel. NEST calculates the return of investment (ROI), internal rate of return (IRR), and net present value (NPV). These merits are used to compare the economics of different types of reactor power plants and other technologies. The following contains the definitions for these concepts [11].

Return on Investment (ROI)

Another criterion often used by investors for comparing alternative investment options is the ROI, which measures *how much money or profit is made on an investment as a percentage of the cost of that investment*. It shows how effective and efficient an investment is in generating profits. The ROI can be calculated as follows [11],

$$\text{Return on investment} = \frac{Gain\ on\ investment - Cost\ of\ investment}{Cost\ of\ investment} \cdot 100 \tag{5}$$

[3] The formula can be found in the NEST Algorithm Step 4 rev 1.0.

[4] The formula can be found in the NEST Algorithm Step 4 rev 1.0.

Internal Rate of Return (IRR)

The IRR is the rate used as discount rate at which the sum of discounted revenues and the sum of discounted costs are equal, the equation of IRR can be expressed as [11]

$$\sum_{t=1}^{t=n} \frac{R_t}{(1+r)^t} = \sum_{t=1}^{t=n} \frac{C_t}{(1+r)^t} \tag{6}$$

If revenues (Rt) and costs (Ct) for each year are known, one can calculate "r" from the above equation, which will represent the IRR. The project with highest IRR will be preferred.

Net Present Value (NPV)

The alternative projects can also be ranked by comparing the present worth of their net profits over their entire life cycle. The preferred equation for the alternative project's present worth of net profits, which is expected to deliver the maximum net profit, is Eq. (7) [11].

$$\text{Present worth of net profits} = \sum_{t=1}^{t=n} \frac{R_t - C_t}{(1+r)^t} \tag{7}$$

where C_t is cost in year t; R_t is revenue in year t; r is the discount rate; and n is the life cycle of the project. For computing this metric, the future revenues are estimated assuming future prices. If the projects are different in size, scaling of the NPV is possible.

2. Evaluation of economic competitiveness of various technologies

The NEST was applied to conduct economic evaluations of innovative nuclear technologies, classic technologies, and renewable energy technologies for electricity generation in this section. Six electricity generation systems were considered. The equations of different technologies to calculate the LUEC differ from each other because they have different sources of fuels and different technologies for operation and fuel management, etc. Based on equation (4), the component of LUEC for different technologies might change a little bit and the expressions for LUAC, LUOM, and LUFC are different[5].

In order to perform the economic assessment to compare the economic parameters of different technologies, an appropriate value for the real discount rate should be considered in accordance with the financial and economic environment, such as 8%.

The economic analysis of different technologies has been performed by using the IAEA's NEST. The input data needed for the calculations is divided into six categories, namely: i) General data; ii) Power plant data; iii) Decommissioning and backfitting data; iv) O&M data; v) Market data; vi) Fuel cycle data. All the input data used to carry out the analysis were public data, from public reports, international projects and public databases. Table 1 and Table 2 present some technical and economic input parameters used for the calculations[6].

Table 1. Technical input parameters

Parameters	Unit	PWR	PWRmox	HWR	FBR	WSPP	FPP
Net electric power	kW(e)	600000	600000	666000	600000	1000000	380000
Construction time	Years	4	4	6	4	2	3
Lifetime of the plant	Years	60	60	35	60	20	40
Average load factor	%/100	0.9	0.9	0.8	0.9	0.3	0.75
Net thermal efficiency of the plant	%/100	0.3093	0.3093	0.3086	0.4	-	-

[5] The formula can be found in the NEST Algorithm Step 4 rev 1.0.

[6] Some of the parameters in the table are referred to the demo case in the online NEST.

Parameters	Unit	PWR	PWRmox	HWR	FBR	WSPP	FPP
Nuclear fuel backend cost [($/kg HM)SF]	$/kg	400	-	73	-	-	-
Spent nuclear fuel average burnup	MWd/kg	40	40	7.5	100	-	-
Reactor average power density	kW/kg	28.89	28.89	23.5	85.07	-	-
Natural U purchase cost	$/kgU$_{nat}$	50	50	50	-	-	
U conversion cost	$/kgHM	8	8	8	-	-	-
U enrichment cost	$/SWU	110	110	0	-	-	-
Nuclear fuel fabrication cost	$/kgHM	275	275	65	-	-	-

Table 2. Economic input parameters

Parameters	Unit	PWR	PWRmox	HWR	FBR	WSPP	FPP
Overnight construction cost	$/kW(e)	1145	1145	1697	1145	1000	376
Fixed O&M cost	$/kW(e)	49	49	54.94	49	0	0
Variable O&M cost	mills/kWh	0.9	0.9	0	0.9	6	6
Tax rate	%/100	0.37	0.37	0.37	0.37	0.37	0.37
Price of unit electricity sold	mills/kWh	61.28	61.28	61.28	61.28	95.00	61.28
Market income	M$/year	3000	3000	3000	3000	0	3000
Market share	%/100	0.5	0.5	0.5	0.5	0	0.5
Profit margin	%/100	0.1	0.1	0.1	0.1	0.0	0.1
Time of growth	Years	6	6	6	6	0	6
Adjusting coefficient	%/100	1	1	1	1	0	1

3. Analysis

This section introduced the economic evaluation results for different electricity generation technologies in terms of LUEC and other financial merits.

Table 3 presents the estimated LUAC, LUOM, LUFC and LUEC for each considered electricity generation system. Among the six systems assessed, the four nuclear technologies had the lowest LUEC. FBR had the lowest LUEC with the value of 31.88 mills/kWh. The LUEC for solar and wind technologies (WSPP) was the highest at 114.47 mills/kWh, followed by the fossil fuel technology (FPP) at 50.22 mills/kWh. The LUEC of HWR is a little higher than PWR and PWRmox.

Table 3. Estimated LUAC, LUOM, LUFC and LUEC for each technology

Parameter	Unit	PWR	PWRmox	HWR	FBR	WSPP	FPP
LUAC	mills/kWh	21.69	21.69	27.29	21.69	65.38	11.37
LUOM	mills/kWh	7.12	7.12	7.84	7.12	6.00	6.00
LUFC	mills/kWh	6.20	8.37	3.56	3.07	0	32.85
LUEC	mills/kWh	35.01	37.18	38.68	31.88	114.47	50.22

Figure 3 displays the pie charts of LUAC, LUOM and LUFC for each electricity generation technology. The LUAC of both PWR and PWRmox account for about 60% of the whole LUEC. For PWR, LUOM accounts for 3% more than LUFC, while for PWRmox, LUFC accounts for 3% more than LUOM, which is due to the different fuel cycles for these two types of nuclear reactors. Among the six technologies, the largest share of LUAC in total LUEC for the HWR technology, accounting for 70.54%, while the smallest share of LUAC in total LUEC is for the FPP, accounting for 22.65%. FPP also had the highest proportion of fuel expenses. For the operation expenses of the six technologies, WSPP has the lowest proportion, which is 5.24%. Because fuel for WSPP is renewable, the LUFC for WSPP is zero.

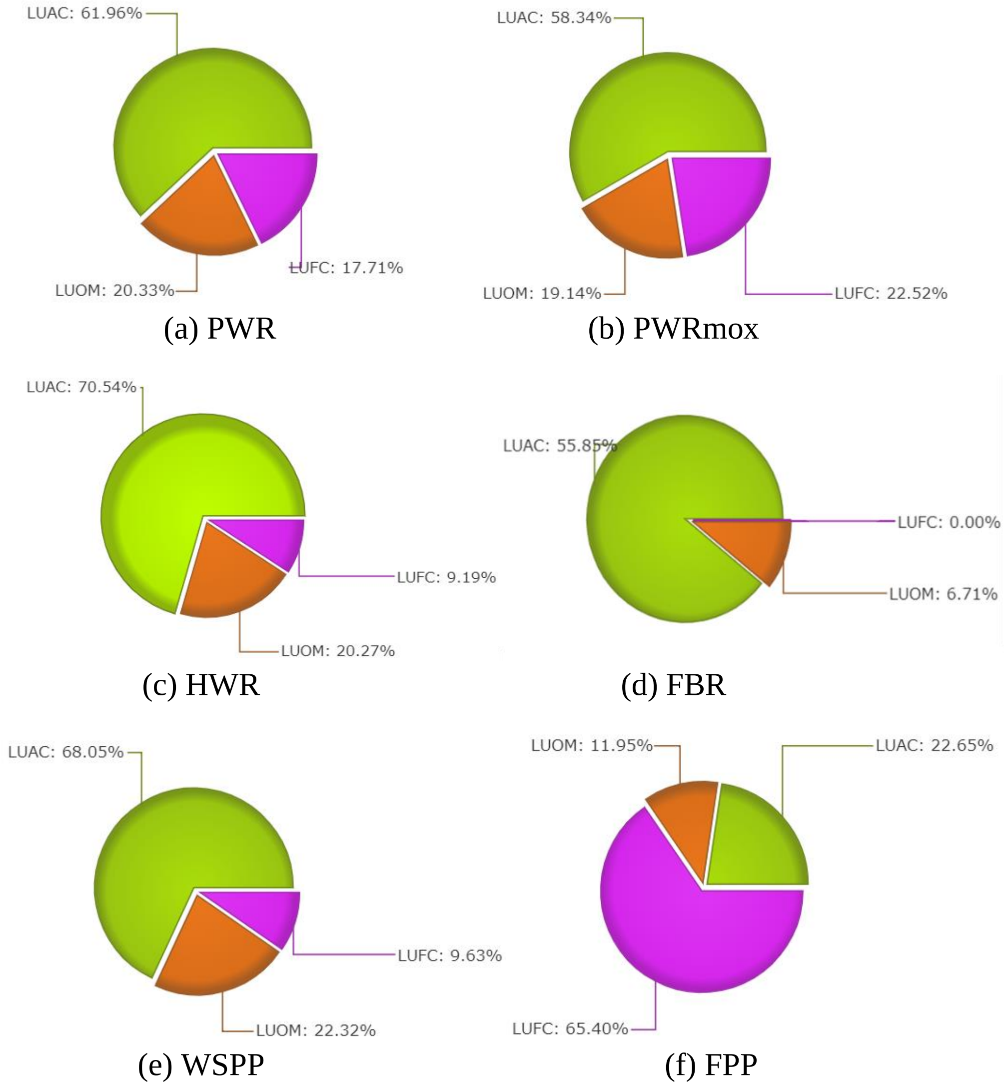

Figure 3. The pie charts of LUAC, LUOM and LUFC for each electricity generation technology.

Figure 4 shows the LUFC components for PWR. The cost of the U-enrichment is the highest. The cost of fuel fabrication, uranium purchase, and back-end costs are similar, each accounting for approximately 20% of LUFC.

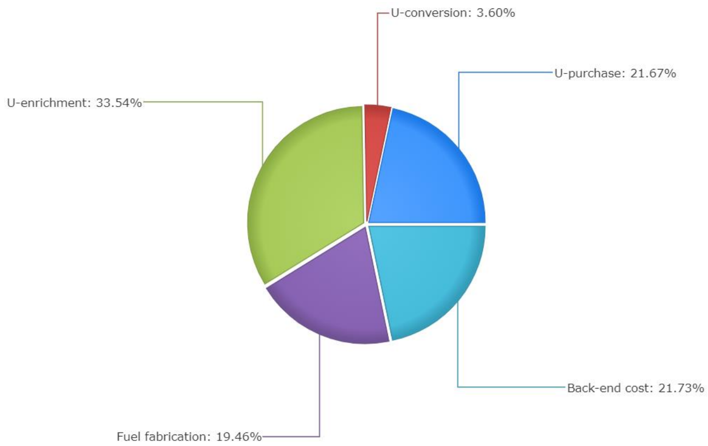

Figure 4. LUFC component of PWR.

4. Results

The results of other merits for the six technologies, in terms of ROI, NPV and IRR, are shown in Figure 5 to Figure 7. Among the six technologies, FBR electricity generation system has the highest ROI, highest NPV, and a relatively high IRR, which is second only to FPP electricity generation. In terms of ROI and IRR, PWR technology is second, followed by PWRmox and HWR. Compared to other electricity technologies, the economic advantages of WSPP are not obvious, which is demonstrated by the lowest ROI, IRR and NPV.

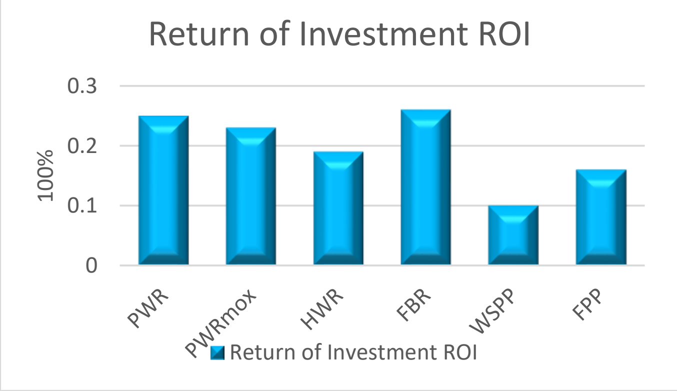

Figure 5. The result of ROI.

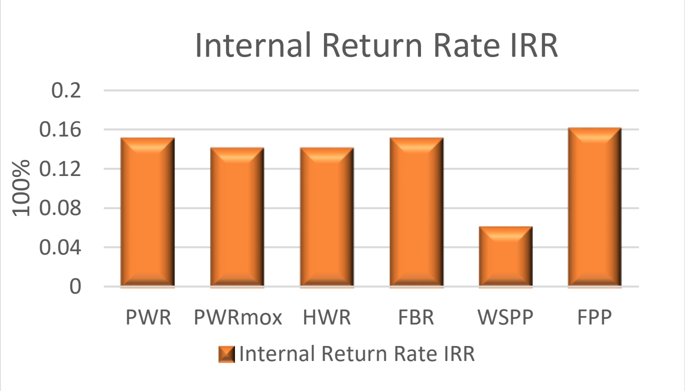

Figure 6. The result of IRR

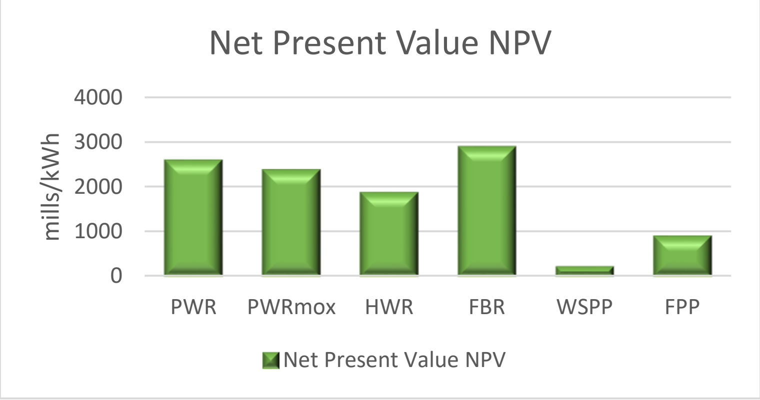

Figure 7. The result of NPV.

The results of the economic evaluation for the six electricity generation technologies confirmed the economic advantages of nuclear technology, demonstrated by a relatively lower LUEC, higher ROI, higher IRR, as well as a higher NPV. Amongst the nuclear technologies, FBR was the cheapest and had the best return merit. This analysis aligns with other studies, such as the United Nations Carbon Neutrality Project [3], and the study of the International Energy Agency [16].

5. Conclusions

Nuclear energy is regarded as one of the important solutions for the sustainable development of energy power. INPRO integrates important aspects of nuclear energy sustainability in six topical areas and developed a methodology for conducting a nuclear energy system assessment (NESA) in each area to confirm the long-term sustainability or identify issues or gaps of nuclear energy systems. The NESA economics support tool (NEST) provides a tool for performing an INPRO sustainability assessment in the area of economics.

This economic evaluation covered six types of electricity generation technologies using NEST, including innovative nuclear reactor technologies, classic technologies with fossil fuels and renewable energy sources. The levelized unit energy cost and its component, as well as other financial merits were calculated and compared. The results showed that nuclear technologies, compared with classic fossil fuels and renewable technologies, have the greatest advantage in terms of economics. In particular, amongst all the technologies considered, the Fast Breeder Reactor (FBR) had the lowest LUEC and highest ROI and NPV. This study demonstrated that the FBR technology in terms of economics is the best electricity generation option.

This analysis also aligns with other studies, such as the United Nations Carbon Neutrality Project and the study by the International Energy Agency (IEA) and the Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA) under the oversight of the Expert Group on Electricity Generating Costs (EGC Expert Group) [16]. This study is also useful for Member States in developing policy frameworks and long-term strategies for sustainable energy in economics, and for evaluating nuclear material management strategies.

Acknowledgement

This work was supported by the International Atomic Energy Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO).

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