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A Study on the Optimal Economic Evaluation Methodology of i-SMR

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1. Introduction

IAEA defines Small Modular Reactors (SMRs) as nuclear reactors with an output of 300MW or less, and with components that are modularized into a single unit, in contrast to traditional large-scale reactor [1]. SMRs are getting attention in the nuclear industry, with over 71 models are under development globally in countries such as South Korea, the United States, Russia, and China [2].

According to the Ministry of Science and ICT(MSIT) and the Ministry of Trade, Industry and Energy(MOTIE), ROK's innovative SMR technology development project passed the preliminary feasibility study in May 2022, and approximately KRW 400 billion ($360 million) will be invested until 2028 for global SMR market in 2030s. SMRs are currently being developed for commercialization within the next decade, and numerous related studies are conducted globally. However, most are focused on technical and safety aspects, with less emphasis on economic feasibility. In order to be competitive, the SMR must be economically feasible. Therefore, it is necessary to study the economic feasibility of SMR through various methodologies.

This paper aims to review various economic evaluation methodologies that are widely used in economic feasibility studies and conclude with an optimal economic evaluation methodology for i-SMR. The evaluation methodologies are reviewed in Chapter 2. In Chapters 3 and 4, case studies of economic feasibility evaluations for traditional large-scale NPP and SMRs, respectively, are examined. Based on the analyses in Chapters 2 to 4, the optimal economic evaluation methodology for i-SMR in ROK is presented in Chapter 5.

2. Economic evaluation methodology

2.1 Net Present Value (NPV) evaluation

Net present value is a method of calculating net present value by discounting a company's free cash flow to firm to its present value and summing them up. If the net present value is greater than 0, it is evaluated as economical [4].

$$NPV = \sum_{t=0}^{n} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \qquad (1)$$

B_t : Benefit at time t
C_t : Cost at time t
r : discount rate
n : Project period (or analysis period)

2.2 Evaluation of Internal Return Rate (IRR)

The internal return rate is a method of calculating the discount rate when the net present value becomes zero. This is called the internal return rate. If the internal return rate is greater than the target rate of return of the project or project, it is evaluated as economical [4].

$$\sum_{t=0}^{n} \frac{B_t}{(1+R)^t} = \sum_{t=0}^{n} \frac{C_t}{(1+R)^t} \qquad (2)$$

R : Internal Return Rate
B_t: Benefit at time t
C_t : Cost at time t
n : Project period (or analysis period)

2.3 Evaluation of Benefit-Cost analysis (B/C ratio)

The Benefit-Cost analysis evaluates the economic feasibility by dividing the discounted benefits by the discounted costs to obtain the B/C ratio. If the B/C ratio is greater than 1, it is considered economically feasible [5].

$$B/C = \frac{\sum_{t=1}^{n} \frac{B_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{C_t}{(1+r)^t}} \qquad (3)$$

B_t : Benefit at time t
C_t : Cost at time t
r : discount rate
n : Project period (or analysis period)

2.4 Evaluation of Payback Period

The payback period evaluation is a method that indicates the period required to recover all of the total costs based on the cash flows generated during the project period, and the formula is as follows [5].

$$\text{Accumulated liquidity}(n) = \sum_{t=0}^{n} cf(i) \qquad (4)$$

$cf(i)$: net income after tax at which cumulative cash flow is zero

2.5 Levelized Costs of Energy (LCOE) evaluation

The levelized cost of generation (LCOE) evaluation is a hypothetical power generation cost that can recover all of the power production costs such as construction costs, O/M, and fuel costs during the lifetime of the generator and the investor's opportunity cost [6].

$$LCOE = \frac{\sum_t (C_t + O/M_t + Fuel_t)/(1+r)^t}{\sum_t GN_t/(1+r)^t} \qquad (5)$$

C_t : Capital cost in year t (construction cost, interest, decommission cost)
O/M_t: Operation and maintenance costs in year t (fixed costs + variable costs)
$Fuel_t$: fuel cost in year t
GN_t : generation at time t
r : real discount rate = WACC

3. Case Study on Economic Evaluation of LR

In 2018, Jo Seong-Jin and Kim Yun-Kyung(2018) calculated the LCOE for Long Term Operation(LTO) of NPPs and compared it with electricity generation cost of new NPP, new coal-fired plant, and new LNG combined cycle power plants proposed in the 7th Basic Plan for Long-term Electricity [6]. Key factors for economic evaluation are investment costs, fuel costs, net O&M costs, decommissioning costs, R&D, PA costs, Local Resource Facility Taxes and etc. LCOE of LTO are derived based on unit cost of key factors and sensitivity analysis are also conducted for the case of discount rates (3/5.5/10%), capacity utilization rates (60/70/80/90%), and continued operation periods (10/20 years).

Table. 1. Generation cost items for LCOE calculation

items	Detailed Contents	Cost per Unit
Investment	Facility replacement cost Safety improvement cost, etc.	Investment Cost /generation
Fuel cost	Annual average fuel cost during LTO	Fuel cost /generation
O/M	Material Cost, Salaries, repair and maintenance costs, and other costs, etc.	Financial cost /generation
Decommission	Medium & low level waste management cost, SpentFuel cost, Decommission cost	Annual average cost/generation
Other cost	R&D cost, Regional cooperation project cost, Local resource facility tax	Cost per generation according to relevant laws

* Economic feasibility study of the life extension (2018)

Lee Ki-hyeon, Kim Tae-ryeong, and Jeong Cheol-wook(2015) evaluated the economic feasibility of LTO of nuclear power plant using the levelized generation cost, and additionally, the number of new nuclear power plant construction and electricity sales that can be replaced assuming LTO of nuclear power plants for 10, 20, and 30 years was calculated [7]. Investment costs, operation and maintenance costs, fuel costs, and decommission costs were considered when calculating equalized generation costs, and the unit sales price of the Korea Power Exchange was used to calculate costs reduced by LTO instead of constructing new nuclear power plants. Sensitivity analysis was performed on the discount rate (3/6/10%), utilization rate (60/70/80/90%), and LTO period (10/20/30 years).

KHNP's own economic evaluation of LTO, unlike studies outside KHNP, mostly utilized the net present value (NPV) method to evaluate the economic feasibility of LTO versus permanent suspension through cash flow comparison [8]. This is because it is possible to access detailed financial datas for estimating annual cash flows, enabling detailed evaluation of expected revenues and expenses during the period of LTO. The purpose of evaluation is not comparison with other power generation sources, but a specific power plant's economic feasibility, therefore it is a comparative study of economic feasibility between LTO and permanent suspension in, it seems that the net present value method is more suitable for the comparison method between alternatives.

For internal decision-making, quantitative economic feasibility according to the selection of alternatives must be presented, but equalized generation cost is not suitable for calculating the economic scale of alternatives because it is a method of estimating the generation cost. This is because an additional sales calculation process is required. For this reason, even in the feasibility evaluation of a general project, the equalized generation cost method is used when the purpose of the evaluation is to compare the economic feasibility of power generation sources, but the net present value method is used to evaluate the feasibility of the project itself.

Table. 2. Cases of economic evaluation of LTO

	Item	evaluation agency	time	Analysis method
1	Wolsung Unit 1	KEPCO EPRI	2009.	NPV
2		KHNP CRI	2013	NPV
3		KHNP CRI	2013	NPV
4		Korea Energy Economics Institute	2014.	LCOE

5	Kori Unit 1	KEPCO EPRI	2006.	NPV
6		KEPCO EPRI	2007.	NPV
7		Korea Energy Economics Institute	2015.	NPV/LCOE

4. Case of SMR economic evaluation

Lee Seul and Jung Woo-yong (2002) designed the LCOE and financial model, and applied Monte Carlo Simulation(MCS) for uncertainties of variables to evaluate economic and financial feasibility of large NPP and SMRs. In the LCOE model, SMR input variables were estimated through the SMR learning curve (Fig. 1) based on the cost of large NPP, and the SMR reduction coefficient which is taken account factors such as lessons learned and modularization, was applied. The financial model considered an increase in financing costs due to the construction schedule change, and presented the financial aspects of SMR, such as interest cost and investment payback period compared to the construction cost [9].

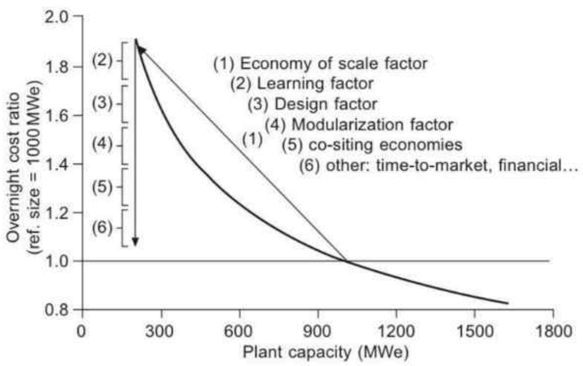

Fig. 1. Top-down calculation of SMR construction costs (Barenghi et al, 2012)

B. Mignacca · G. Locatelli (2020), through Systematic Literature Reviews, comprehensively summarized factors required to be considered for evaluating the economics of SMR. The economic evaluation of SMRs requires consideration on the capital cost (construction and financing cost during construction period usually takes about 50-75% of the total cost), as well as O&M costs, fuel costs, and decommissioning costs. When estimating Overnight Construction Cost of SMRs, the size ratio with large NPP and the modularization effect must be taken into account. It was also pointed out in the paper that reduced financing cost due to the reduced construction schedule, as well as cost savings from scale factors and repeated construction needs to be considered. O&M cost reduction by multiple unit concept and decommissioning cost reduction due to modular concept were also mentioned[10].

5. i-SMR economic evaluation methodology

In this chapter, based on the review results of Chapters 2 to 4, the optimal economic evaluation methodology for i-SMR will be discussed.

For economic feasibility of i-SMR, depending on the evaluation purpose, two evaluation methodologies could be used. For comparing i-SMR with different generation source, LCOE is applied as it estimates generation cost. While NPV is more appropriate for financial evaluation such as profitability during the operation period as NPV considers interest rate change over time and detailed cash inflow/outflow.

5.1 LCOE evaluation

In order to calculate the LCOE of i-SMR, four factors, capital cost, fuel cost, O&M cost, and decommissioning cost must be considered.

$$LCOE = \frac{\sum_t (C_t + O/M_t + Fuel_t)/(1+r)^t}{\sum_t GN_t/(1+r)^t} \quad (6)$$

5.1.1 Capital cost

There is big difference in cost estimation in each countries due to market and business environment. In regulated market such as ROK, financing cost is relatively lower than non-regulated market, as the government is leading the business. In addition, repeated construction experience is highly likely to contribute reducing construction cost. Therefore, it is important to postulate an appropriate capital cost for ROK environment.

As i-SMR is currently under development, no construction cost record is available. Therefore, for estimation of construction cost, two methods are suggested. 1) Using existing construction cost (Large NPP) by sub-dividing it and use scale factor for relevant items. 2) Using construction cost suggested by KHNP.

Option 2) could be more precise as it is based on undisclosed data of the company. During preliminary feasibility study of i-SMR technology development project, an expected construction cost was published.

For estimation of construction cost, financing cost for the total construction cost must be considered. This can be calculated by the difference in total cost between the present and the future by talking into account construction schedule and completion. For accurate calculation, financing portion in total construction cost could be taken into consideration.

5.1.2 Fuel Cost

KHNP previously announced that it aims to enable i-SMR for longer cycle (more than two years) by increasing enrichment assay. As it means a different fuel assembly will be loaded, using the existing fuel cost from large NPP might cause an error in calculation.

In addition, price might vary depending on fabricators. Therefore, due to uncertainty, three scenarios, import, domestic production, and using scale factor are neccessary to analyze.

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5.1.3 O&M

An average of O&M cost of large NPP is used, but it is necessary to review each item whether the cost difference between the existing NPP and i-SMR occurs and calculate a proportional value based on this. Items to be reviewed include labor costs, repair and maintenance costs, development costs, taxes, and other expenses. For each item, the ratio might vary depending on their characteristics.

For labor costs, unlike conventional large NPP, i-SMR with innovative technologies can be operated only by a small number of operators. Therefore, for labor cost estimation could use ratio of number of operators in large NPP and i-SMR.

For development costs, R&D funds are determined by existing NPP under the Nuclear Promotion Act but i-SMR can be excluded as non-related costs or calculated based on the assumption that the same development costs are paid. Taxes also do not incur because related laws are not currently in place. However costs can be derived by assuming the same law is going to be applied.

O&M costs are expected to incur at a relatively low cost by innovative technologies and regulatory environments, it is appropriate to use Bottom-Up method as described above.

5.1.4 Decommission

Decommissioning costs needs to use existing NPP cost but recalibration is required depending on the regulatory environment. Decommission costs consist of Low and Intermediate Level Waste (LILW) disposal costs, Spent Fuel(SF) management charges, and demolition work costs. For LILW, the waste volume is likely decrease compared to large NPP due to boron-free concept and simplified systems. The amount of SF generation is also expected to decrease through long-term operation (more than two years). Therefore, same as O&M cost discussed in 5.1.3, it would be appropriate to use bottom-up method.

Since the cost of demolition work is also likely to decrease due to modularized system concept, the cost reduction rate can be estimated and applied through meta-analysis of related studies.

5.2 Financial Assessment

In the evaluation of the feasibility, Capital costs, fuel costs, operating maintenance costs, and decommissioning costs that were reviewed in LCOE should be considered using NPV methodology. Additionally, each cost 1) needs to consider inflation for respective operating period and 2) analyses their cash flows with discount rate, and 3) estimates NPV.

5.2.1 Electricity sales price

The sales price of electricity generated should be calculated differently, depending on the operator. In case KHNP is an operator, it is appropriate to use the nuclear power unit electricity sales price assuming that the current power market system is maintained. However, in case an operator is not KHNP, sales are going to be made by a separate difference transaction contract. In such case, the contract price is required for further review.

5.2.2 Considering Uncertainty

The i-SMR input variable for evaluation at this stage is highly uncertain. Therefore, for accuracy, it is necessary to perform sensitivity analysis on fuel cost, utilization rate, sales price, discount rate, etc. Alternatively, the other way would be to present the distribution range of the results through Monte Carlo simulation using a probability function.

5.2.3 other benefits & costs

In the economic evaluation of i-SMR, in addition to the items previously discussed, there are others that need to be addressed. When evaluating economic feasibility, other profits obtained from electricity system could be considered as well. Other profit includes the following items;

As i-SMR could be used as a disperse power source, transmission lines is not required and therefore transmission line cost could be excluded and considered a profit. In addition, i-SMR could generate additional profits, such as auxiliary service costs and Positive DR as DR resources, which can be obtained as compensation for intermittent operation of renewable energy in the electricity market. The greenhouse gas reduction effect, which is a traditional benefit item, may also be considered as a profit. However, since social benefit items cannot be viewed as direct profit, it might not be appropriate to include them in financial assessment.

6. Conclusions

Several countries around the world are promoting SMR projects due to its advantages such as location, safety and technical advancement. As development is currently underway, many studies are focused on technology and safety. However, from the perspective of countries consider SMRs, economic feasibility is the key. Budget overrun of Vogtle NPP in the US is nearly as twice of initial plan, and France's Flamaville is suffering from the same issue. The problem is not much different in the SMR field. Recently, NuSclae Power's LCOE was adjusted by 53%, 58$/MWh to 89$/MWh [12]. It would be difficult to expect a success of a project with ambiguous economic feasibility. In other words, in the market, NPP with economic feasibility could survive. Therefore, the economic feasibility of SMR should also be considered a critical factor from now.

In future study, an actual LCOE will be estimated by using the economic evaluation methodology presented in this paper, and the economic feasibility will be reviewed through financial evaluation.

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