Economic Feasibility Simulation of Large reactors and SMRs

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1. Introduction

Many issues regarding Large-scale nuclear power plants(LR) are being discussed due to the rising financial risk caused by high initial investment costs and construction delays and concerns about the impact of an accident[1,2,7]. Small Modular Reactors(SMR) development is accelerating, especially among nuclear power generation leaders, to compensate for the risks of existing LR. For this reason, many previous studies conducted a comparative analysis of Levelized cost of electricity(LCOE) economic feasibility between LR and SMR[2,4,6]. However, in the case of LCOE, it is difficult to determine profitability during the life cycle of the plant construction business[3]. An important factor in economic analysis is the calculation of income and expenses. Therefore, it is necessary to effectively calculate the cost required from construction and the income obtained by selling the generated electricity to the electricity market. Therefore, this study intends to review both economic comparison studies through LCOE and financial models. Although the analysis result may vary depending on the input assumption, this study aims to understand which variables have a large influence and how much improvement in SMR can exceed the economic feasibility of LR, rather than focusing on the exact numerical value of the result. In addition, it provides new insights based on the results analyzed and describes limitations and future research.

2. Methods

In this section, the LCOE model and financial model are simulated to consider uncertainty about various parameters through the Monte Carlo Simulation (MCS). MCS is a method that approximates a result by conducting countless repeated experiments through random number generation when a certain problem is given [5]. In this study, MCS is performed 5000 times.

2.1 LCOE Model

The LCOE equation(1) is modified to reflect the SMR reduction factor(3). Detailed cost calculation for SMR is currently not possible; input variables are estimated through a bottom-up approach.

LCOE ($/MWh)

$$= \frac{\{(OCC \times SRF) \times CRF + F\_O\&M\}}{8{,}760 \times \text{Capacity Factor}} + FC \times HR + V\_O\&M \quad (1)$$

- OCC : Overnight Construction cost($/kWh)
- CRF: Capital Recovery Factor(%)
- F_O&M : Fixed O&M Cost($/kW-year)
- V_O&M : Variable O&M Cost($/MWh)
- FC : Fuel Cost($/MMBtu)
- HR : Heat Rate(Btu/kwh)

Using the lifetime and interest rate can calculate a Capital Recovery Factor (CRF). The CRF is used to calculate the present value of a sequence of yearly cash payment [3,5].

$$CRF(\%) = \frac{i(1+i)^n}{[(1+i)^n] - 1} \quad (2)$$

- i : Interest Rate(IR, %)
- n : Lifetime(LT, years)

Each input variable is modeled based on the open literature. Table I, II are a summary of the input values of LCOE. The lifetime of LR and SMR is assumed to be the same as 60 years. IR have a significant impact on LCOE and are applied differently depending on the country. In this LCOE model, 3% and 7% IR is used to reflect various market conditions. An IR of 3% represents a relatively stable market and low-risk project, while an IR of 7% is a value given to a project with a relatively high risk in an unstable market and volatile conditions[3].

Table I: LR Input variables

	Distribution	Min	Mean	SD	Max	Ref
OCC	Normal		3393	890		3,7
FOM	Normal		75	11		3
VOM	Triangular	0.42	1.28		2.14	3
CF	Uniform	85			90	3,5
LT	Uniform	60			60	7
FC	Uniform	0.6			0.67	3,5
HR	Uniform	10450			10480	3,5

Table II: SMR Input variables

	Distribution	Min	Mean	SD	Max	Ref
OCC	Normal		5000	3900		1,4
FOM	Normal		90	36.9		2,4
VOM	Triangular	0.5	1.54		3.5	2,4
CF	Uniform	85			90	3,5
LT	Uniform	60			60	1,2
FC	Uniform	0.6			0.67	3,5
HR	Uniform	10450			10480	3,5

SMR's cost estimates are generally calculated through the SMR learning curve(Fig. 1.), based on the reference cost of a large nuclear power plant(PWR)[2].

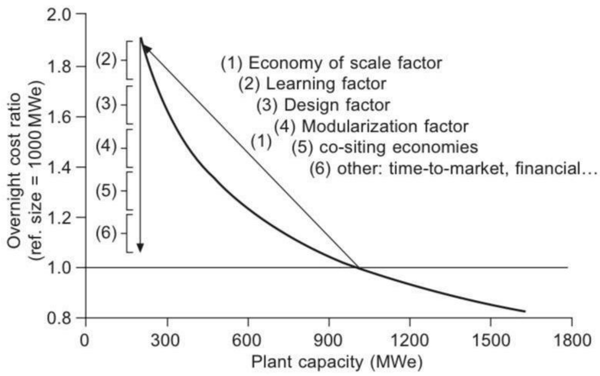

Fig. 1. Top-down estimation of overnight construction cost of SMR : qualitative trend(Barenghi *et* al., 2012)

SRF is constructed based on five factors as shown in Equation (3) and applied to the LCOE equation.

SMR Reduction Factor(SRF)
=Economies of scale × Learning Factor × Design Factor × Modularization Factor × Co_siting Factor (3)

In this study, SRF is considered taking into account the characteristics of First-of-a-kind(FOAK) and Nth-of-a-kind(NOAK)(Table III). In addition, based on the distribution graph results, a detailed analysis of the economic feasibility of SMR is attempted by calculating the LCOE frequency of SMR, which has a lower value than LR.

Table III: SMR Reduction Factor

	LR	SMR(F)	SMR(N)
Reduction Factor(%)	100	103.33	85.37

2.2 Financial Model

Financial model is developed to compare economic competitiveness with LCOE calculation by conducting a financial feasibility analysis for each power plant of LR and SMR. The longer the nuclear power plant construction period, the greater the financial cost and the negative impact on the project cost. The financial model shows the difference in project cost and financial costs according to the power plant and construction period. For input variables of the financial model, LR uses some modified financial values in the A, B, C projects. In order to match the total power output with the LR(1400 MW), it is assumed that five SMR units with a capacity of 300 MW will be constructed. Construction period is assumed to be 5 years for LR and 4 years and 2 years for SMR FOAK and SMR NOAK, respectively. IR is compared by setting 3% and 7% in the same way as LCOE.

In order to further analyze profitability, the shareholders' payback period is also calculated using Net Present Value (NPV), which represents the present value of the investment.

3. Results

3.1 LCOE

Fig. 2, 3 shows the probabilistic distribution graphs when the interest rate is 3% and 7% of IR. Red represents the LCOE distribution at the LR. And the blue and green distribution graphs represent FOAK SMR and NOAK SMR, respectively. As a result of the distribution graph analysis, the LR graph is skewed to the left in both the case of 3% and 7% of IR, which means that the LCOE value is the lowest. Additionally, it appears to be the most competitive overall since, when compared to the other two SMR graphs, the distribution width of LR is the narrowest. The LCOE of NOAK SMR, however, falls below that of FOAK SMR as IR rises from 3% to 7%. Additionally, it is apparent that the SMR distribution width and the portion of the SMR that overlaps with the LR grow as IR increases.

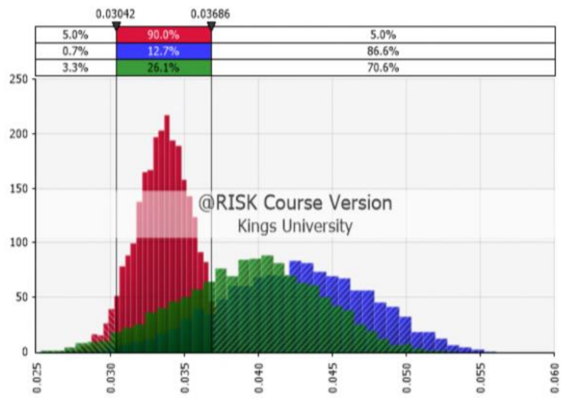

Fig. 2. LCOE distribution of LR(Red), FOAK SMR(Blue), NOAK SMR(Green) at 3% of IR

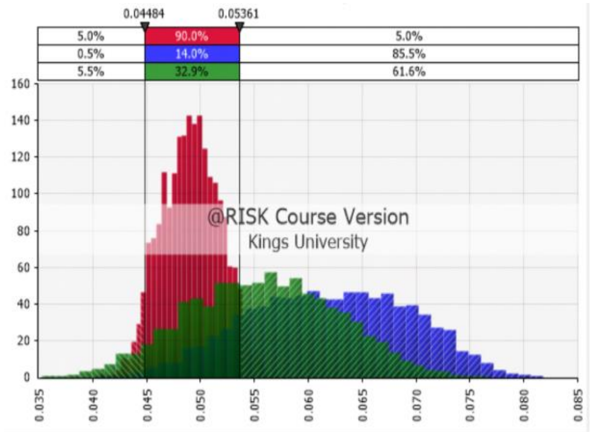

Fig.3. LCOE distribution of LR(Red), FOAK SMR(Blue), NOAK SMR(Green) at 7% of IR

Table IV: LCOE values at 3% and 7% IR

IR	LR	SMR(F)	SMR(N)
3%	33.65$/MWh	41.85$/MWh	38.47$/MWh
7%	49.15$/MWh	60.73$/MWh	54.07$/MWh

As a result of the additional frequency analysis, FOAK SMR results show similar values when the IR is 3% and 7%(Table V). However, in the case of NOAK SMR, among the 5000 simulations, the probability of getting a smaller LCOE value than LR is 14% and 18% at 3% and 7% of IR. It can be seen that as the IR increases, the ratio of SMR to an advantageous position compared to LR increases.

Table V: SMR LCOE frequency

	(a)3%	(b)7%	(a)/5000	(b)/5000
SMR(F)	283	268	0.056	0.053
SMR(N)	709	904	0.141	0.180

3.2 Financial

In each power plant, the higher the IR and the longer the construction period, the greater the financial cost, which seriously affects the project cost. In particular, the result of calculating the Total Interest Cost (TIC)/OCC of LR when IR reaches 7%, the TIC exceeds the OCC cost, which negatively affects the project. However, in the case of SMR, the ratio does not exceed 100%. In general, SMR has a lower TIC/OCC ratio than LR, showing that although SMR has higher capital costs than LR, financial costs are stable and affordable.

Table VI: TIC/OCC and PB at 3%, 7% of IR

	IR(%)	TIC/OCC(%)	PB(years)
LR	3	39.45	18
	7	109.90	39
SMR(F)	3	37.16	28
	7	93.02	Unable to payback within the period
SMR(N)	3	32.80	11
	7	87.89	25

In addition, as a result of calculating the equity payback period, the payback period(PB) increased as the IR of all three types of power plants increased. In the case of FOAK SMR, it is found that it would be difficult to pay back within the period when it is 7% IR. However, in the case of NOAK SMR, the PB is shorter than LR. Reducing Payback period itself has a great advantage in that it can reduce investor risks.

4. Conclusions

This study conducts economic, financial comparisons of LR and SMR through various analysis methods. As a result, the economic feasibility of large nuclear power plants seems to be far ahead of SMR. However, it is shown that if the SMR reduction factor is improved due to technology development, and in the case of NOAK SMR, the higher the interest rate, the more stable the huge financial cost flow and can cope better than LR. This suggests that the issue of investment risk in large nuclear power plants can be supplemented. However, since there is still a high gap with LR, more measures will need to be taken to achieve economically viable SMR construction. Although this study is conducted based on open literature values, all input variables are made with assumptions because there is no practical SMR yet. Also, the energy grid and energy capacity needs are not taken into account. It is expected that more quantitative values can be obtained if economic and financial comparisons are made by supplementing these limitations in the future.

Acknowledgement

This research was supported by the 2022 Research Fund of the KEPCO International Nuclear Graduate School (KINGS), the Republic of Korea.

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