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Overall generation cost analysis according to the SMR units in Jeju Island

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1. Introduction

Currently, load following operation of Jeju Island is totally depended on the importing electricity from the mainland. The electricity import cost in Jeju is generally more expensive than the generation cost in the island, reduction of importing electricity is a significant task to enhance the financial situations of Jeju's energy institution. This study assumed that the Small Modular Reactor (SMR) can contribute to the reducing of dependency of electricity import by operating load following mode. In order to utilize the SMR in Jeju as load following power source, SMR's load following operation should be economically competitive. The competitiveness of SMR can be evaluated by comparing the total generation cost according to the load following scenario. This study introduces the methodology of the load following scenario modeling at the method section. The different load following scenario was achieved according to the number of SMR units. Hence, this paper analyzed the total generation cost in terms of SMR units in Jeju (i.e., in terms of load following scenario).

The concept of Levelized Cost Of Electricity (LCOE) is introduced in order to calculate total generation cost. This study explained the concept of SMR's LCOE in method section, and compared the total generation costs according to the load following scenario and discount rate in result section. The load following scenarios of SMR are calculated by the Linear Programming Method (LPM). The LPM's calculation progress of SMR's load following scenario is summarized in method section.

The result of total generation cost comparison indicates the three SMRs are the optimal case because of the lowest total generation cost. Such results are valid for the general discount rate conditions (3, 5%), because of the high potion of investment cost in SMR's LCOE.

2. Method

This section introduces the methodology to calculate total generation cost according to the load following scenario of SMR. The load following scenario of SMR is significantly varied according to the number of units. This section is organized by three sub-sections. First, mathematical description of SMR's load following scenario modeling based on LPM. Second, SMR's LCOE is explained. The calculation method of total generation cost is explained in the third sub-section.

2.1 Load following scenario modeling of SMR

This study assumed that the amount of renewable energy and baseload power generated prior to the construction of the SMR is the same as the amount generated after the construction of the SMR, because of the SMR's short construction period (3 years). Therefore, it is still valid to use current power data of renewable and baseload power to predict the electricity generation after the SMR's installation.

Currently, baseload mode is occupied by fossil power plants, and load following mode is occupied by HVDC (High Voltage Direct Current) system in Jeju. Therefore, energy balance equation of Jeju can be derived as (1).

$$P_{t,d} = \eta\left(P_{t,HVDC} + P_{t,ren} + P_{t,f}\right) \quad (1)$$

where P, η are power and power loss coefficient, subscriptions t, d, $HVDC$, ren, f are time, demand, HVDC, renewable, and fossil.

We can derive a new energy balance equation (2) when SMR ($P_{t,SMR}$) is installed.

$$P_{t,d} = \eta\left(P_{t,HVDC} + P_{t,SMR} + P_{t,ren} + P_{t,f}\right) \quad (2)$$

The P_d, P_{ren}, P_f are significantly varied according to the season, the P_{SMR} and P_{HVDC} are significantly varied according to the season (see Fig.1). This study uses the recorded data of P_d, P_{ren}, P_f. The unknowns (P_{SMR}, P_{HVDC}) are derived by using LPM for representative seasons in Jeju.

The grid system pursues to generate the electricity with the satisfaction of minimum generation cost for the given condition. This study applied LPM to solve (2), because LPM has the qualified performance to solve the cost minimization problem [1]. Such minimal generation cost constraint could be expressed as (3).

$$\text{minimize} \sum_{t=1}^{24} LCOE_s P_{t,s} \quad (3)$$

where subscription s means the power source index.

Since the P_{ren}, P_f are not varied for the different number of SMR, (3) can be re-written as (4).

$$\text{minimize} \sum_{t=1}^{24} LCOE_{SMR}P_{t,SMR} + LCOE_{HVDC}P_{t,HVDC} \quad (4)$$

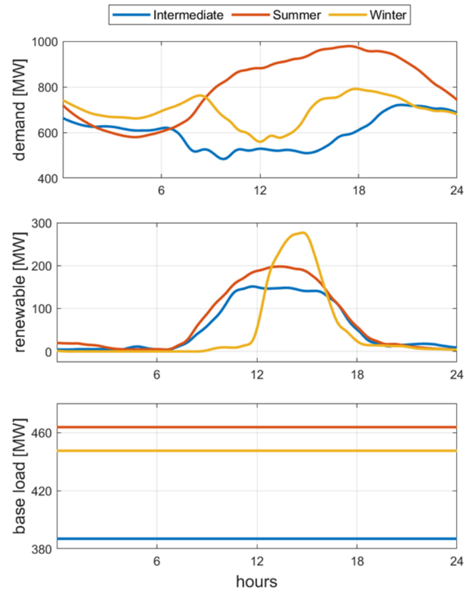

Fig. 1. Demand and baseload for renewable power profiles according to season

The power boundary, ramp constraints are applied to LPM in order to achieve more realistic generation scenario of SMR. Table I listed the constraints and required parameters for LPM. Since the constraints of LPM are varied according to the number of SMRs, we could achieve the SMR's load following scenarios according to the SMR units.

Table I: Constraints and parameters for LPM

	SMR	HVDC
Lower power limit (%)	15 [3]	0
Upper power limit (%)	100	100
Ramp limit (%/min)	5 [2]	10
LCOE ($/MWh)	> 92	92*
Total capacity (MW)	121 per unit [2]	500
Number of units	[1, 5]	-

*Data source: EPSIS

2.2 SMR's LCOE

The LCOE is a significant factor that effects on the total generation cost. Reminding that the baseload, renewable powers are given variables, such variables can't affect to the total generation cost. Since the HVDC's LCOE is given in Table I, the last variable to calculate overall generation cost is SMR's LCOE. This study defined SMR's LCOE by four cost terms; investment cost (I_y), variable O&M cost ($O\&M_{V,y}$), fuel cost (F_y), and decommissioning cost (D_y) as (5).

$$LCOE_{SMR} = \frac{\sum_y \frac{(I_y + O\&M_{V,y} + F_y + D_y)}{(1+d)^y}}{\sum_y \frac{E_y}{(1+d)^y}} \quad (5)$$

where E, d are generated electricity and discount rate, and subscription y means the year. The required variables for the organization of (5) are achieved from the technical reports for SMR [3, 4].

2.3 Total generation cost

Total generation cost is a key parameter for the decision of load following scenario. This study assumed the optimal load following scenario of SMR should enable the lowest total generation cost. Hence, this section introduces the methodology of total generation cost derivation according to the SMR's load following scenario. The total generation cost (GC_t) from power source is generally defined as (6).

$$GC_t = \sum_{t=1}^{24} LCOE_s P_{t,s} \quad (6)$$

The generation costs from baseload and renewable powers are neglected, because such costs have the same values for the scenarios. Therefore, (6) can be expressed as (7) for Jeju case.

$$GC_t = \sum_{t=1}^{24} LCOE_{SMR}P_{t,SMR} + LCOE_{HVDC}P_{t,HVDC} \quad (7)$$

At last, total generation costs are compared according to the load following scenario of SMR (i.e., number of SMR) and discount rate conditions.

3. Results

The series of LPMs are carried out according to the different number of SMRs (see Table I). The load following scenario of SMR is derived according to the number of SMRs (see Fig. 2).

The SMR's LCOE are captured in Table II according to the number of SMR units and discount rates.

Table II: SMR's LCOEs according to number of SMRs (N) and discount rates

Scenarios	Discount rate (%)			
	3	5	7	10
LCOE, $N = 1$, ($/MWh)	43	58	75	106*
LCOE, $N = 2$, ($/MWh)	45	60	79	112*
LCOE, $N = 3$, ($/MWh)	48	65	86	123*
LCOE, $N = 4$, ($/MWh)	54	75	100*	144*
LCOE, $N = 5$, ($/MWh)	64	91	122*	178*

*LCOE that is higher than HVDC transmission cost

The achieved LCOE shows the minimal result for the single SMR unit, because the generated electricity per unit of SMR is decreased as the installed SMR units are increased (see Fig. 3).

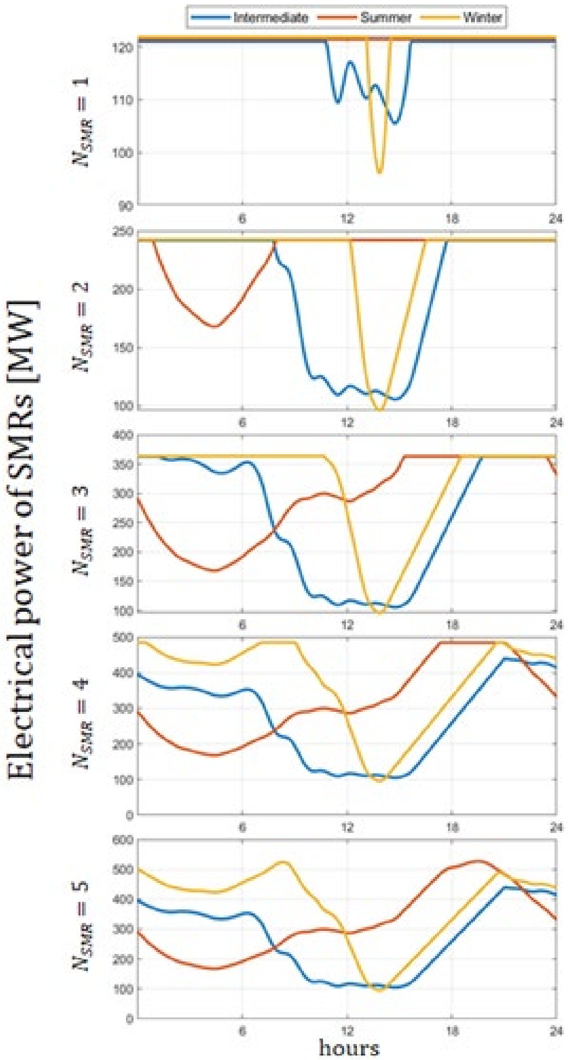

Fig. 2. Result of power generation from SMRs according to the SMR units (calculated by LPM)

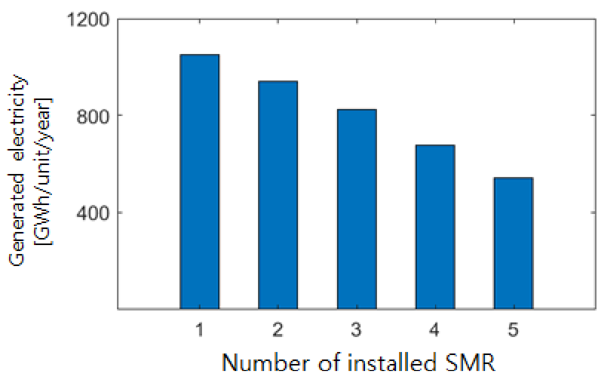

Fig. 3. Result of power generation from each SMR according to the SMR units

The Table II shows that the SMR's LCOE becomes more expensive than the HVDC's transmission cost at the high discount conditions (7, 10%). However, such discount conditions are not general cases, SMR installation is economically valid if business planner can avoid such cases.

Based on the SMR's LCOEs, the total generation costs are captured according to the SMRs and discount rate conditions in Table III.

Table III: Total generation costs according to number of SMRs (N) and discount rates

Scenarios	Discount rate (%)			
	3	5	7	10
$GC_t,\ N = 0,\ (1e5\$/day)$	7.3	7.3	7.3	7.3
$GC_t,\ N = 1,\ (1e5\$/day)$	5.9	6.3	6.8	7.7
$GC_t,\ N = 2,\ (1e5\$/day)$	4.8	5.6	6.6	8.3
$GC_t,\ N = 3,\ (1e5\$/day)$	4.3	5.5	6.9	9.4
$GC_t,\ N = 4,\ (1e5\$/day)$	4.5	5.8	7.6	10.8
$GC_t,\ N = 5,\ (1e5\$/day)$	4.9	6.8	8.9	12.9

The three SMRs have the minimal generation costs for the general discount rate conditions (3, 5%) as we highlighted in Table III. Since the general SMR's LCOE is cheaper than HVDC, the SMR's generation replaces the transmission from the HVDC. Consequently, total generation is dramatically decreased from single unit to three. However, the more units than three shows the more total generation cost than three, because too much capacity of SMR is allowed for the amount of demand (see Fig. 4, 5).

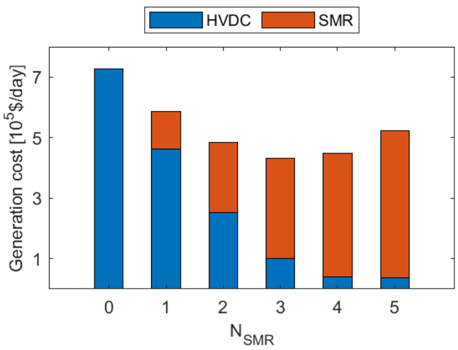

Fig. 4. Result of total generation cost for discount rate 3%

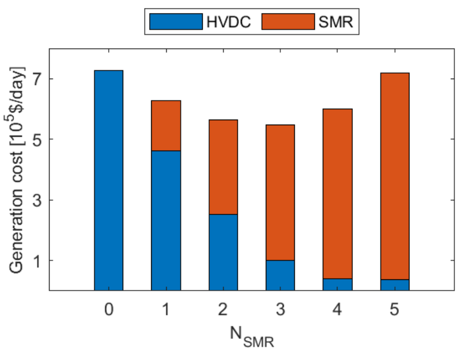

Fig. 5. Result of total generation cost for discount rate 5%

4. Discussions

This study analyzed the total generation cost in terms of number of SMRs and discount rate conditions. Since the different generation scenarios should be formulated according to the number of SMRs, LPM is introduced to calculate load following scenario of SMR. The result shows that the three SMRs can generate the electricity with the minimal total generation cost (see Table III). This means that the SMR installation in Jeju can reduce the total generation cost, and such cost reduction has the maximum effect for the three SMRs case.

The more electricity generation from SMR means to replace the power transmission from HVDC. SMR's electricity generation with load following operation could contribute to the lowering the Jeju's electricity dependency on the import from mainland.

The deployments of SMR could contribute to the reduction of carbon dioxide emissions. Fig. 6 shows the more SMRs reduces the more carbon dioxide emissions. The amount of carbon dioxide emissions is dramatically decreased by three SMRs. However, increasing number of SMRs more than three is very inefficient for the reducing carbon dioxide emissions. Therefore, three SMRs are the most desirable number in terms of total generation cost and carbon dioxide reduction aspects.

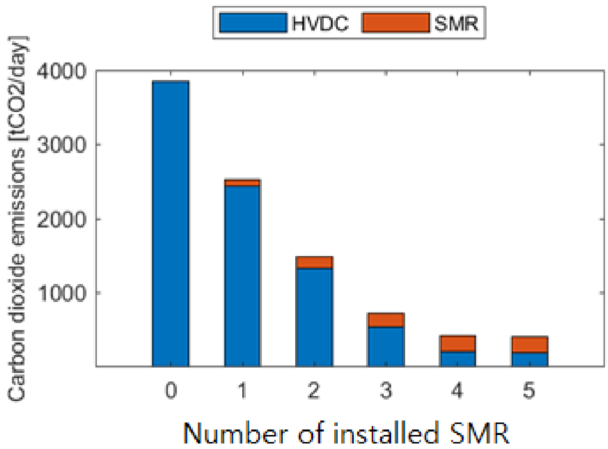

Fig. 6. Result of carbon dioxide emissions according to the installed SMRs in Jeju

5. Future Work

This work assumed the constant generation scenarios for baseload and renewable power sources even after the installation of SMRs. As a result, achieved minimal total generation cost (for three SMRs) is not considered the renewal of baseload and renewable power generations. Total generation cost might be decreased by re-arranging the generation scenarios of baseload and renewable powers. Especially, Jeju Island's generation cost of baseload powers (liquefied natural gas, oil) are generally very expensive.

This study achieved the multi-units of SMR provides the minimal total generation cost. The load following operation of each SMR is assumed to be identical. The SMRs' load following scenario is based on the LPM with reactor's operational constraints. Such constraints could be overcome by differently operating the each SMR. The operational method of each SMR for multi-units of SMR should be prepared.

Acknowledgement

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REFERENCES

[1] Vanderbei, Robert J. Linear programming. Springer International Publishing, 2020.
[2] KHNP, KAERI, KACARE, SMART100 Standard Safety Analysis Report, 2019.
[3] Mignacca, Benito, and Giorgio Locatelli. "Economics and finance of Small Modular Reactors: A systematic review and research agenda." Renewable and Sustainable Energy Reviews 118 (2020): 109519.
[4] OECD. Current Status, Technical Feasibility and Economics of Small Nuclear Reactors, Organization for Economic Co-Operation and Development, 2011.