Energy Share Optimization of Concentrated Solar Power and Nuclear Hybrid System

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1. Introduction

Small Modular Reactor (SMR) has many advantages, for example, flexibility of the construction, compactness in footprint and application for a distributed power. At the same time, a supercritical CO_2 (S-CO_2) Brayton cycle is in the spotlight due to the relatively high efficiency at moderate heat source temperature (500-600°C) and compact components [1]. To couple these two technologies, KAIST research team developed a small modular reactor named KAIST MMR (Micro Modular reactor), using the merits of S-CO_2 Brayton cycle and SMR (Small Modular Reactor) [2].

Recently, renewable energy is also expanding in the energy market due to growing interest in the need to reduce CO_2 emissions for addressing global warming issue. However, renewable energy sources always require a backup power system to overcome the intermittency issue. Therefore, KAIST research team is now developing KAIST-HMMR (Hybrid Micro Modular Reactor), a new convergence system that combines KAIST-MMR with CSP (Concentrated Solar Power) to cover the electricity demand successfully with non-carbon emitting energy sources. The CSP system uses a mirror or lens to focus large area of the sunlight to generate solar energy.
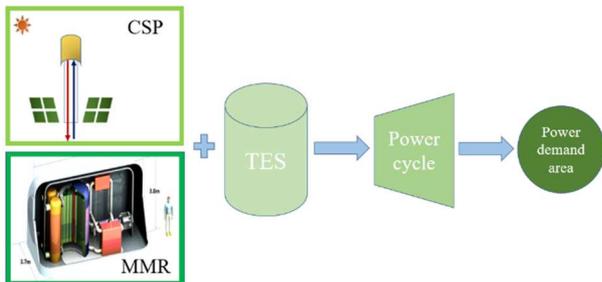

Figure 1. Concept of the Hybrid MMR(KAIST-HMMR)

The HMMR enables more flexible and efficient production and supply of energy in accordance with the demand of electric power through the hybrid system. Load-following operation is easy to perform due to TES (Thermal energy storage). The TES is added to the HMMR to compensate for the intermittency of the CSP while satisfying the electric power demand of the target region. In this study, the optimization of Nuclear (MMR) power to CSP ratio is first discussed. This is followed by determining the capacity of TES for the candidate region.

2. Methods and Results

2.1 Selection of the target region

The required solar field area for CSP and TES capacity vary depending on how much CSP can generate at the target region for the same electricity demand. Therefore, long-term trends of more than 10 years data of solar radiation and sunshine hours should be first reviewed [3].

South Korea data for sunshine hours and solar radiation is first reviewed. It is also selected as an example of mid - latitude area where HMMR can be installed. Furthermore, the region with the highest potential for CSP development was chosen within Korea by referring to the data of Korea Meteorological Agency [4]. As a result, considering the sunshine hours and the daily normal irradiation, it was confirmed that Jinju area is the best areas for CSP development in Korea.

2.2 Demand curve prediction

To model hourly electricity demand, the electricity demand can be approximated with the Gaussian distribution. The maximum, minimum, average values and standard deviation can be adjusted for the modeling purpose. The Gaussian distribution for demand modeling is as follows, where μ is the mean value, σ is the standard variation.

$$f(x|\mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \qquad (1)$$

To determine the coefficient, first, the minimum and the maximum values of the original hourly electricity demand is obtained, and each value is selected to satisfy the base and the peak modeled electricity demand which the electricity demand was approximated with the Gaussian distribution. Second, an average of the original electricity demand values is used as for the modeled electricity demand. Third, the standard deviation was calculated using equation (2) to make a Gaussian distribution shape while maintaining the maximum and the minimum values of the original electricity demand.

$$\sigma_{ed} = \frac{\mu_{ed} - ed_b}{\sqrt{2\pi}(ed_p - ed_b)} \qquad (2)$$

where σ_{ed} is the standard variation of the modeled electricity demand, μ_{ed} is the mean value of the modeled electricity demand which is the same value of the original electricity demand. ed_b and ed_p mean the base and peak

modeled electricity demand respectively. Finally, the obtained electricity demand is expressed by the peak time of the original electricity demand, t_p.

$$\text{For } 0 \leq x \leq t_p, f(x) = LC \times \frac{1}{\sqrt{2\pi\sigma_{ed}^2}} e^{-\frac{(x-(p_t-24))^2}{2\sigma_{ed}^2}} \quad (3)$$

$$\text{For } t_p \leq x \leq 24, f(x) = LC \times \frac{1}{\sqrt{2\pi\sigma_{ed}^2}} e^{-\frac{(x-p_t)^2}{2\sigma_{ed}^2}} \quad (4)$$

$$LC = \frac{Local\ population}{National\ population} \times (\mu_{ed} - ed_b) \times 24 \quad (5)$$

In Korea, the original electricity demand can be obtained from the KPX site. Therefore, the average electricity demand in Korea can be calculated, and the average electricity demand in Jinju was obtained by multiplying ratio of Jinju city population to South Korea population. The average electricity demand in the Gaussian distribution is shown in the following figure and the area under the graph is integrated to calculate the required daily electricity demand of the region. Jinju has a daily electricity demand (E_{Demand}) of 9514 MWh of electricity.

Table1. The value of the demand curve with gaussian distribution for Jinju

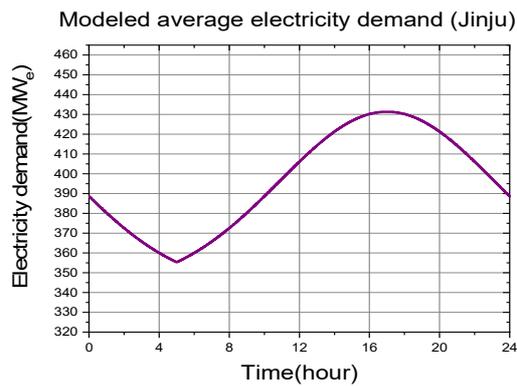|	Jinju
ed_b(MW$_e$)	355.36
ed_p(MW$_e$)	431.34
μ_{ed}(MW$_e$)	399.26
σ_{ed}	32.65
p_t(hour)	17

Figure 2. Average electricity demand approximated with gaussian distribution – time graph for Jinju

2.3 DNI calculation

Based on the electricity demand model, base electricity demand and peak electricity demand were obtained. Since the design of HMMR uses nuclear power as a base heat source with constant heat output, the base electricity demand is assumed to all nuclear power.

To obtain the output of the CSP, the value of the direct normal Irradiation (DNI) should be obtained and it is calculated by the hourly beam irradiation of the region. Therefore, in order to obtain a theoretical result for obtaining the hourly beam irradiation (I_b) , KAIST_HMD code was developed by the following method suggested in Ref. [5]. To calculate beam irradiation per hour, it is necessary to obtain the total daily irradiation (H).

The daily total irradiation (H) has the following relationship and can be obtained by inputting the latitude of the region and the monthly average extraterrestrial irradiation (H_0) of the region, where K_T is the clearness index.

$$H = K_T H_0 \quad (6)$$

Second, the daily diffuse irradiation (H_d) which is calculated as follows should be obtained, where w_s is the sunset hour angle

$$\text{For } w_s \leq 81.4°, If\ K_T < 0.715,$$
$$\frac{H_d}{H} = 1 - 0.2727K_T + 2.4495K_T^2 - 11.951K_T^3 + 9.3879K_T^4$$
$$\text{else, } \frac{H_d}{H} = 0.143 \quad (7)$$

$$\text{For } w_s \geq 81.4°, If\ K_T < 0.715,$$
$$\frac{H_d}{H} = 1 + 0.2832K_T - 2.5557K_T^2 + 0.8448K_T^3$$
$$\text{else, } \frac{H_d}{H} = 0.175 \quad (8)$$

The ratio of the total daily irradiation to the total daily irradiation (r_t) and the ratio of daily to total daily irradiation and the ratio of hourly diffuse to daily diffuse irradiation (r_d) can be obtained as follows. w is the hour angle of the sun.

$$r_t = \frac{I}{H} = \frac{\left(\frac{\pi}{24}\right)[a+bcos(w)][cos(w)-cos(w_s)]}{\left[sin(w_s) - \frac{\pi w_s cos(w_s)}{180}\right]} \quad (9)$$

$$r_d = \frac{I_d}{H_d} = \frac{\left(\frac{\pi}{24}\right)[cos(w)-cos(w_s)]}{\left[sin(w_s) - \frac{\pi w_s cos(w_s)}{180}\right]} \quad (10)$$

The hourly diffuse irradiation (I_d) and the hourly global irradiation (I) can be obtained from the above. The hourly beam irradiation (I_b) is calculated by the following equation. Therefore, the beam irradiation amount per hour for one year is calculated as shown in the following figure.
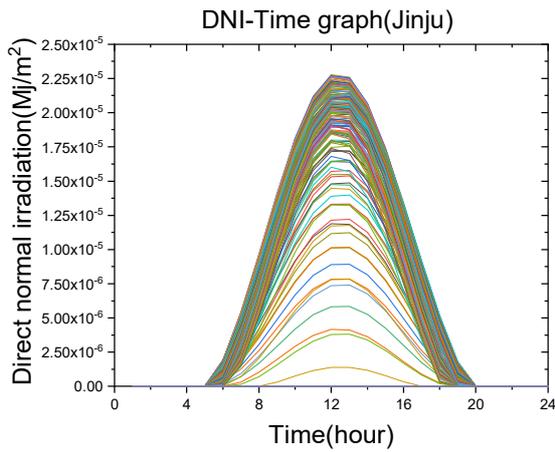
$$I_b = I - I_d \quad (11)$$

Figure 3. DNI -Time graph (Jinju)

2.4 Optimized Nuclear and CSP Contribution

It is important to determine the ratio of the nuclear power and CSP in order to effectively meet the regional demand. In this study, the minimum value of electricity demand will be covered by nuclear power and the other electricity demand will be covered by CSP. Therefore, the electricity demand for CSP and TES is calculated as follows.

$$E_{demand,CSP} = E_t - E_{base} \qquad (12)$$

Where $E_{demand,CSP}$ = electricity demand covered by the CSP per day (MWh), E_t = total electricity demand per day (MWh) and E_{base} = electricity demand covered by the MMR per day (MWh).

Therefore, the ratio of CSP and MMR in the selected region is as follows, and R_{CM} = CSP / MMR can be calculated.

Table 2. Electricity demand of the CSP, MMR and Ratio of CSP and MMR for Jinju

Jinju	*Electricity demand (*MWh)
CSP	985.21
MMR	8528.6
R_{CM}	12%

2.5 Solar heat and required area

The hourly heat output of CSP (Q_{CSP}) can be obtained by hourly beam irradiation and the following formula.

$$Q_{CSP} = I_b \times A_{sf} \times \eta_{HF} \times \eta_{rec} \times (1 - \eta_{parastic}) \qquad (13)$$

The daily electricity demand covered by CSP for region($E_{demand,CSP}$) and the hourly heat output have the following relationship and it is possible to calculate the required area of CSP.

$$E_{demand,CSP} = \int Q_{CSP} \, dt \times \eta_{piping} \times \eta_{storage} \times \eta_{cycle} \qquad (14)$$

The above equation can be changed as follows.

$$E_{Demand,CSP} = \eta_{solar} \times P_{DNI} \times A_{sf} \qquad (15)$$

Where $P_{DNI} = \int_0^{24} I_b \, dt$, $\eta_{solar} = \eta_{HF} \times \eta_{rec} \times \eta_{piping} \times \eta_{storage} \times \eta_{cycle} \times (1 - \eta_{parastic})$

Each of the above efficiencies(η) can be obtained by referring to the following reference.

Table 3. The overall efficiency of the solar component

Component	Efficiency	Ref
Solar field (η_{HF})	48-50%	[6]
TES ($\eta_{storage}$)	>99%	[6]
Power block (η_{cycle})	~40%	[6]
Receiver (η_{rec})	<<1%	[5]
Piping (η_{piping})	<1%	[5]
Parastic ($\eta_{parastic}$)	~10% (maximum)	[7]

Based on the above table, η_{solar} was determined to be 17%. Therefore, if P_{DNI} is calculated by integrating I_b, required area to generate the solar power(A_{sf}) can be calculated.

Table 4. The daily electricity demand covered by CSP and required *solar area for only CSP and HMMR for Jinju*

Jinju	Only CSP	CSP+MMR (HMMR)
$E_{Demand,CSP}$ (MWh)	9514	985.21
A_{sf} (m²)	9.23×10^8	9.56×10^7

2.6 TES Thermal Sizing

Since the required electricity demand of CSP is calculated, the output of CSP graph can be obtained by using the previously calculated distribution of I_b because *and*, A_{sf} are fixed constants. Therefore, the HMMR graph can be obtained as follows using the modeled electricity demand. The graph is shown for the case of CSP Only for the comparison between the hybrid system and the conventional CSP only system.
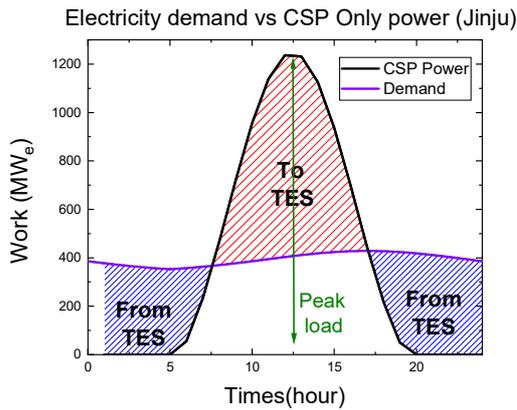
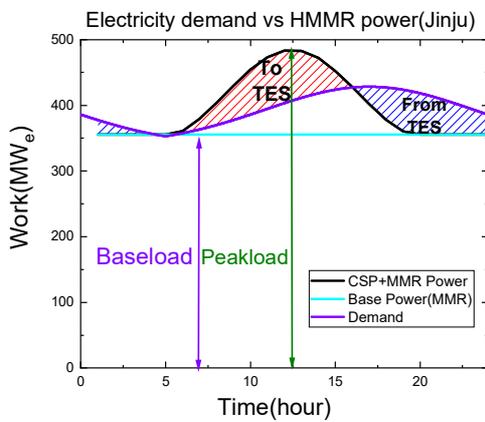Figure 4. Electricity demand vs CSP Only power graph (Jinju)

Figure 5. Electricity demand vs HMMR power graph (Jinju)

To calculate the TES capacity, the relationship between the electricity demand curve and the output of CSP or HMMR is required. In Figures 3 and 4, the area under the electricity demand curve and the area under the CSP or HMMR output curve are the same. Thus, if the electricity demand curve is lower than the CSP or HMMR output, the amount of heat stored in the TES is the excessive amount. Therefore, the intersection points of the graphs in Figures 4 and 5 were first obtained, and the TES capacity was calculated by subtracting integration of the electric demand curve and the output of CSP or HMMR between the two intersections.

Table 5. Intersection of the graph and TES capacity of the CSP Only, HMMR for Jinju

Jinju	Intersection	
CSP Only	7.58	17.06
HMMR	5	15.91
Jinju	TES capacity (MWh)	
CSP Only	2.25×10^3	
HMMR	439.86	

3. Conclusions

In this study, the ratio of nuclear power to CSP and the required TES capacity for CSP Only and HMMR were calculated respectively. In Jinju city, the optimum ratio of nuclear power to CSP was 1: 0.12. Regarding TES capacity, CSP Only requires 2250MWh while HMMR requires 439.86MWh, respectively in Jinju City. Therefore, it is confirmed that the TES capacity of HMMR is 5.11 times smaller than that of CSP Only. In addition, the solar reflector area of CSP is reduced by 10 times for HMMR. As a result, when HMMR is used in comparison with the case of CSP Only case, there is an advantage in terms of cost by reducing required area to generate the solar power and TES capacity size. Also, it can be seen that the power can be adjusted flexibly according to the power demand of the region rather than using only nuclear power.

Further studies will explore how the results obtained in the mid-latitude region will be compared to those obtained in the vicinity of the equator. Design of TES, heat integration of nuclear and CSP, and power cycle optimization will be performed as the next research step.

ACKNOWLEDGEMENTS

REFERENCES

[1] Steven A. Wright, Ross F. Radel, Milton E. Vernon, Gary, E. Rochau, Paul S. Pickard, "Operation and Analysis of a Supercritical CO_2 Brayton Cycle, Sandia National Laboratories, Sandia Report", SAND2010-0171.
[2] S. G. Kim, et al., Conceptual System Design of a Supercritical CO_2 cooled Micro Modular Reactor, Proceedings of ICAPP, 2015.
[3] J.K. Angell and J.Korshover, Quasi-Biennial and Long-Term Fluctuations on Total Ozone, AMS100, 1973
[4] 태양에너지 최적 활용을 위한 기상자원 분석 보고서, 기상청, 200
[5] H.L. Zhang, J. Baeyens, "Concentrated solar power plant: Review and design methodology, Renewable and Sustainable Energy Review, 2013
[6] Wemer Vogel, Henry kalb, Large-Scale Solar Thermal Power: Technologies, Costs and Development, pp.233
[7] Sargent and Lundy Consulting Group, assessment of parabolic trough and power tower solar technology cost and performance forecasts, National Renewable Energy Laboratory, 2003.