Feasibility Study of Large-scale Alkali Metal Thermal Energy Storage

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1. Introduction

Jeju Island has set forth the vision of “Carbon-Free Island Jeju (CFI2030),” aiming to meet 100% of its electricity demand with renewable energy by 2030. In pursuit of this goal, the capacity of renewable energy generation facilities has been expanding rapidly; however, the pace of power grid connection expansion has not kept up, leading to serious curtailment issues. Output curtailment occurs when electricity consumption cannot accommodate the level of generation, leading to downward adjustments in the minimum output of fossil-fuel power plants as well as forced shutdowns of wind and solar power facilities. This arises from the intermittent nature of renewable energy sources—namely, the variability of generation depending on wind speed and solar irradiance—which poses challenges to the stable operation of the power grid.

There is an urgent need for new solutions that can economically store and utilize large-scale electricity, which is not only essential for addressing curtailment issues but also for establishing a stable renewable energy-based power system. In our previous studies[1-4], we carried out a conceptual design of a large-scale thermal energy storage (TES) system, characterized by key features such as a supercritical CO_2 (sCO_2) partial reheat cycle, an air-cooled cooler, a sodium-based thermal storage, and a two-tank system. TES is widely recognized as a promising alternative within energy storage systems (ESS), offering advantages such as minimal installation constraints, environmental compatibility, long-duration storage capability, extended lifetime, and economic feasibility. Among various storage media, sodium is particularly attractive due to its high thermal stability, which allows operation at temperatures above 600°C and enables higher power generation efficiency when coupled with a sCO_2 power cycle. Furthermore, the sCO_2 Brayton cycle has been identified as a more efficient, simpler, and more compact alternative to the conventional superheated steam cycle [5].

In this study, we evaluate the feasibility of introducing TES as a potential solution to the persistent curtailment problem in Jeju. The technical performance of alkali metal-based TES is evaluated using Dymola modeling and simulation, and its economic feasibility is analyzed based on the levelized cost of electricity (LCOE).

2. Methods and Results

2.1 Dynamic Analysis Model

Fig. 1 shows the Dymola model integrating the thermal energy storage and utilization systems. The model represents key components, including pumps, compressors, and heat exchangers, and incorporates controllers for actuators such as pumps and valves. Generators and a grid model are included to convert turbine-delivered mechanical energy into electricity.

A hierarchical control structure is implemented, where the supervisory controller compares grid power demand with generator output to issue start or stop signals. These signals determine the operating modes of subordinate controllers, which manage specific components such as the sodium flow in the TES system, turbine inlet and bypass valves, inventory, and cooler systems. The control logic of each subordinate controller is adjusted according to the operating mode under supervisory control, ensuring coordinated operation of the integrated system.

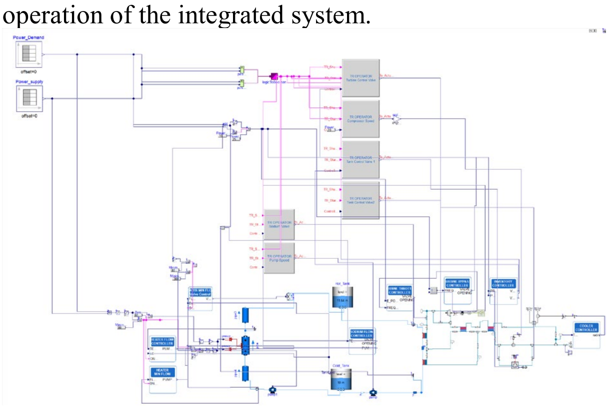

Fig. 1. TES and power conversion system model for dynamic analysis

2.2 Performance Evaluation of TES for Jeju Island

The performance analysis of the thermal energy storage and utilization system was conducted using a representative 216-hour dataset from 2024, including power curtailment, generation, and demand data for Jeju. A representative day from the dataset is illustrated in Fig. 2, where power demand is depicted as a single curve, and total power supply is the sum of LNG, oil, bio-oil, solar, and wind generation. During daytime periods when supply exceeds demand, curtailment actions were applied to wind and solar generation, indicated by hatched regions in the figure.

The TES and utilization systems operate based on the supply-demand balance: when demand exceeds supply, the utilization system generates electricity; when supply exceeds demand, excess power is stored as thermal energy in the TES system. Key performance variables, including electrical output, generation frequency, and sodium tank levels, are presented in Figs. 3–5. Generation frequency was maintained very stably within 60 ± 0.2 Hz, and the system response to output fluctuations was 5%/min, indicating satisfactory dynamic performance. The maximum generation output reached 37 MW, with a corresponding generation efficiency of about 37%.

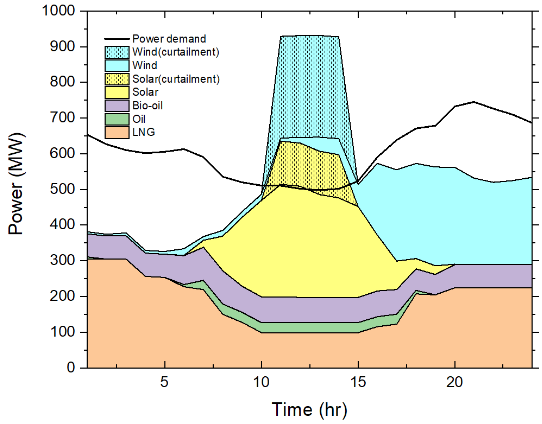

Fig. 2. Daily power demand and supply profile in Jeju

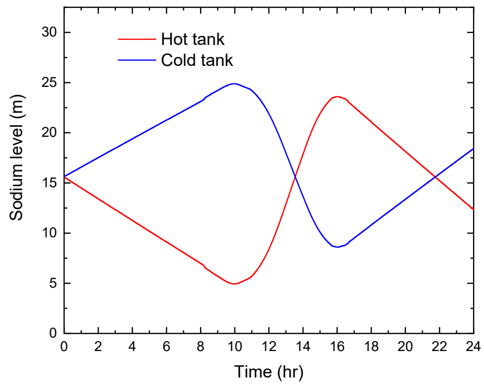

Fig. 3. Daily variation of sodium levels in hot and cold tanks

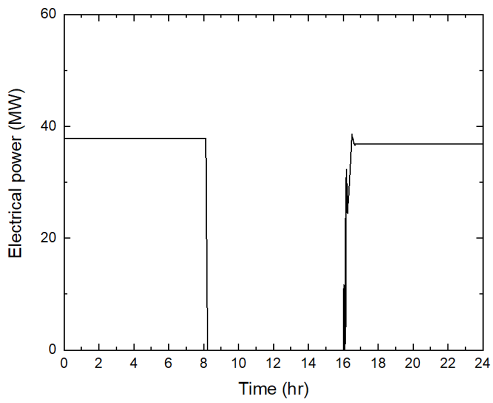

Fig. 4. Daily variation of electrical power

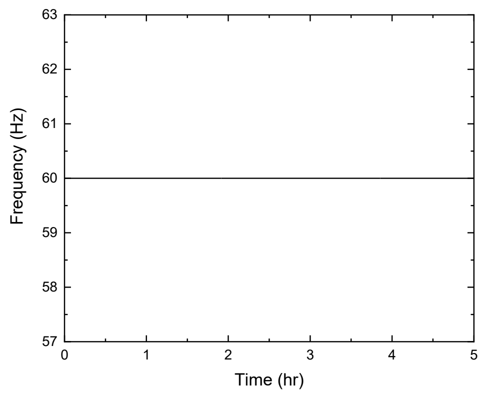

Fig. 5. Daily variation of generation frequency

2.3 Preliminary Economical Analysis Based on LCOE

In the analysis presented in Section 2.2, it was assumed that all curtailed renewable energy on days when curtailment occurs is stored as thermal energy. By determining the maximum daily tank level change, the required TES tank size for Jeju was estimated. The maximum tank level change was 23.4 m, corresponding to a thermal storage capacity of 2.01 GWh. Based on representative curtailment cases in Jeju, the average daily stored thermal energy was calculated as 1.45 GWh. Considering an estimated 200 days of annual curtailment, the total annual thermal energy storage was 289.59 GWh. Assuming a generation efficiency of 37%, the total annual electricity generation from the TES system in Jeju was estimated to be 107.15 GWh in 2024.

LCOE was calculated by dividing the total lifecycle cost of a power plant by its total electricity output. In Eq. (1), t denotes the year (t = 0, initial investment; t ≥ 1, operational years), N the plant lifetime, *CAPEX* the capital cost, *OPEX* the operation and maintenance cost, *FC* the fuel cost, *DC* the decommissioning cost, *EG* the annual electricity generation, and r the discount rate used to convert future cash flows to present value.

$$LCOE = \frac{\sum_{t=0}^{N} \frac{CAPEX_t + OPEX_t + FC_t + DC_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{EG_t}{(1+r)^t}} \tag{1}$$

A plant lifetime of 30 years and a discount rate of 2% were assumed. Although the sCO_2 Brayton cycle offers higher efficiency and more compact equipment than the steam Rankine cycle, its costs are uncertain due to limited demonstration; therefore, this study conservatively adopts the Rankine cycle capital cost assumptions for TES LCOE calculations [6]. The LCOE of a gas-fired power plant was evaluated to replace the 107.15 GWh of annual electricity generated by the thermal energy storage system. Assuming LNG fuel with a 35% thermal efficiency, producing 107.15 GWh annually requires 27.4×10^6 m³ of LNG, which, at a price of 1,200 KRW/m³, corresponds to an annual fuel cost of 32.9 billion KRW. The battery lifetime is assumed to be 15 years, half of the 30-year design life of the thermal energy storage system;

therefore, the CAPEX was doubled, and a round-trip efficiency of 90% was assumed [7].

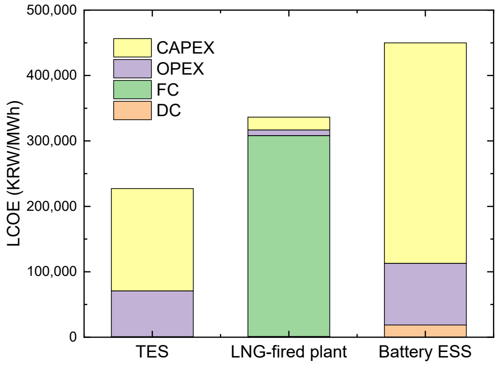

Fig. 6 LCOE comparison study

Based on the LCOE comparison study (Fig. 6), the thermal energy storage (TES) system is the most economical among the analyzed power sources, with LCOEs of gas-fired generation and battery ESS being 48.1% and 98.0% higher, respectively. Although the TES system's CAPEX and associated OPEX are approximately eight times higher than those of gas-fired generation, it requires no fuel during operation, resulting in a lower LCOE. The battery ESS also operates without fuel costs but has a CAPEX more than twice that of the TES system, contributing to a higher LCOE.

For the TES system, CAPEX and OPEX account for 68.8% and 30.8% of the total LCOE, respectively, while fuel and decommissioning costs are negligible. In gas-fired generation, fuel costs dominate, comprising 91.3% of the LCOE. The battery ESS shows a similar LCOE composition to TES, but with a reduced share of OPEX and an increased share of decommissioning costs.

As a zero-carbon power source, the TES system emits no greenhouse gases, unlike gas-fired generation, thereby mitigating the primary contributors to global warming. This characteristic also reduces potential costs associated with future carbon taxes. Furthermore, by avoiding dependence on imported fossil fuels, TES provides a more stable and resilient electricity supply against international market fluctuations.

Battery ESS exhibits the highest generation cost among the options and raises safety and environmental concerns. High energy density increases the risk of fire or explosion during rapid charge–discharge cycles or internal short circuits, with larger-scale systems posing greater hazards and necessitating additional cooling and fire suppression measures. Environmentally, battery manufacturing involves various hazardous materials, and the growing volume of spent batteries exacerbates recycling and disposal challenges.

3. Conclusions

This study comprehensively evaluated the technical performance and economic feasibility of an alkali metal-based thermal energy storage and utilization system to address the intermittency challenges arising from the increasing share of renewable energy in Jeju. Dymola-based modeling and simulation using actual power data from the region demonstrated that surplus electricity otherwise curtailed could be stored as thermal energy, averaging 1.45 GWh per day and approximately 289.59 GWh annually, which enables the generation of an additional 107.15 GWh of electricity per year. Economic analysis based on the levelized cost of electricity (LCOE) showed that the thermal storage system is 48.1% and 98.0% less expensive than gas-fired power plants and battery ESS, respectively, making it the most cost-effective option. Overall, alkali metal-based thermal energy storage and utilization systems can significantly enhance grid stability in Jeju, efficiently utilize otherwise wasted energy, and offer an economically viable solution for large-scale renewable energy integration.

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REFERENCES

[1] H. Y. Ye, J. Hong, D. Kim, Y. Jung, S. Choi, and J. Eoh, Storage Tank Design and Dynamic Analysis of sCO2 Power Conversion System for Thermal Energy Storage System, Transactions of the Korean Nuclear Society Spring Meeting, May 9-10, 2024, Jeju, Korea.
[2] H. Y. Ye, J. Hong, D. Kim, Y. Jung, S. Choi, and J. Eoh, Parametric Study on the Application of Air-cooled Cooler to the sCO2 Cycle, The 13th Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety, Nov. 10-13, 2024, Seoul, Korea.
[3] H. Y. Ye, J. Hong, D. Kim, Y. Jung, S. Choi, and J. Eoh, Dynamic Analysis of sCO2 Power Conversion System for Thermal Energy Storage Systems, The 13th Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety, Nov. 10-13, 2024, Seoul, Korea.
[4] H. Y. Ye, S. Choi, J. Hong, Y. Jung, D. Kim, and J. Eoh, Thermodynamic Analysis of a Thermal Energy Storage System Coupled with a sCO2 Power Cycle Using an Air-cooled Cooler, Trans. Korean Soc. Mech. Eng. B, Vol. 48, No. 12, pp. 795-803, 2024.
[5] V. Dostal, M. J. Driscoll, P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, Advanced Nuclear Power Technology Program, MIT-ANP-TR-100, 2004.
[6] S. Lundy, Capital Cost and Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies, Retrieved from Washington, DC, 2024.
[7] R. I. Areola, Integrated Energy Storage Systems for Enhanced Grid Efficiency: A Comprehensive Review of Technologies and Applications, Energies, Vol. 18, No. 7, p. 1848, 2025.