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Techno-economic analysis of steam generation and energy storage via carnot battery and heat pump: a study based on the levelized cost of heat and storage

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Abstract

The Carnot battery is a long-duration energy storage system (ESS) that converts and stores electrical energy in the form of thermal energy. The stored heat can later be reused for electricity generation, making the Carnot battery a promising technology for retrofitting coal-fired power plants into green storage plants under carbon-neutral policies. Furthermore, the Carnot battery can also be utilized for industrial steam production. This study compares the economic feasibility of steam production using the Carnot battery and heat pump technologies based on the Levelized Cost of Heat (LCOH). In this research, LCOH [$/ton] is used to evaluate the cost of producing industrial steam. The Carnot battery enables thermal energy storage using low-cost nighttime or surplus electricity, resulting in an LCOH less than half of the current industrial steam price. Similarly, heat pump-based steam generation using surplus electricity achieves comparable cost reductions. However, when operated during daytime hours, the heat pump yields an LCOH approximately 10% higher than the market steam price. This study also evaluates the economic feasibility of electricity storage when retrofitting coal-fired power plants with Carnot batteries, based on the Levelized Cost of Storage (LCOS). Additionally, a comparative analysis of combined heat and power (CHP) plant retrofitting was conducted. The economic feasibility of steam production and electricity storage was evaluated according to the steam-to-electricity output ratio, based on both LCOH and LCOS. It was found that retrofitted CHP plants can achieve a lower LCOS compared to standalone coal plant retrofits. Overall, the comparative analysis of LCOH and LCOS in this study demonstrates that thermal energy storage and supply systems based on the Carnot battery and heat pump will become increasingly competitive in the context of global decarbonization and electrification trends.

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1. Introduction

Global efforts are being made to achieve carbon neutrality by 2050. To reduce carbon emissions, the global energy landscape is shifting from fossil-fuel-based energy production toward renewable electricity generation. In this transition, the electrification of both energy demand and supply networks is becoming increasingly important. Moreover, as renewable electricity generation continues to expand, excess power is often produced during periods when supply exceeds demand. Therefore, advanced energy storage system (ESS) technologies capable of absorbing surplus electricity are required to ensure grid stability and efficient utilization of renewable energy [1].

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Among the various technologies proposed to address this issue, the Carnot battery has emerged as a promising long-duration, large-scale, and low-cost energy storage technology. It converts electrical energy into high-temperature thermal energy using devices such as electric heaters or heat pumps and later reconverts the stored heat into electricity when needed (Fig. 1). Carnot battery systems, also referred to as pumped thermal energy storage (PTES), have been studied as a promising option for large-scale and long-duration energy storage. Early studies demonstrated the feasibility of converting electricity into high-temperature thermal energy and reconverting it into electricity using heat pump and thermal engine cycles [2], while later work systematically classified and evaluated a wide range of such PTES concepts for grid-scale applications [3-4]. Owing to its scalability, the Carnot battery can store electricity on the order of several hundred megawatts for more than ten hours, effectively mitigating the intermittency of renewable energy. Furthermore, since the system stores energy in thermal form, the stored heat can be directly utilized for industrial steam production as well as for power generation.

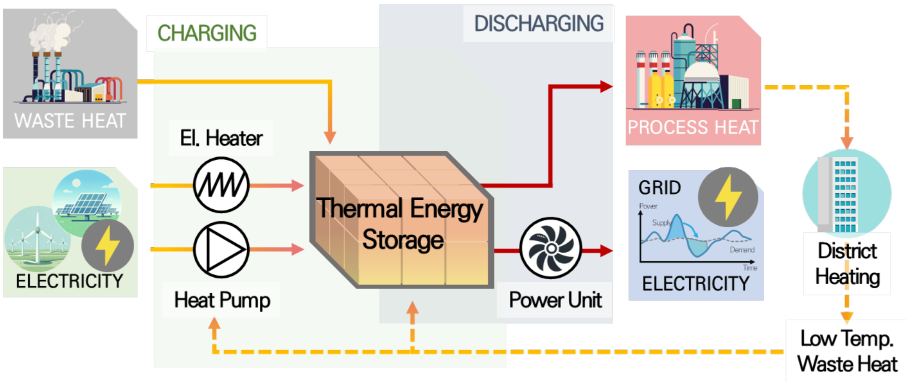

Figure 1. Schematic of the Carnot Battery System

In our recent research, a thermal energy storage system for the Carnot battery is currently being developed [5]. This system is based on a sand–AlSi composite medium (Si 12.6 wt.%, melting point 577 °C). Incorporating AlSi as a phase change material (PCM) within the sand matrix enables stable steam generation when applied to retrofitting coal-fired power plants. The techno-economic assessment of the Carnot battery in this study was conducted based on this thermal energy storage system.

Accordingly, the economic feasibility of industrial steam production using the Carnot battery was evaluated in terms of the Levelized Cost of Heat (LCOH), which accounts for capital investment, operating costs, and energy conversion efficiency. The LCOH of a Carnot battery system utilizing electric heaters was compared with that of a heat pump-based steam generation system to assess the competitiveness of thermal energy storage and supply systems under a future decarbonized and electrified energy environment.

Additionally, this study analyzed the economic feasibility of retrofitting coal-fired power plants with Carnot batteries for electricity storage using the Levelized Cost of Storage (LCOS). A comparative techno-economic analysis was also conducted for Combined Heat and Power (CHP) plant retrofits, evaluating both steam and electricity production based on LCOH and LCOS indicators. Through these analyses, the study aims to identify the cost competitiveness and potential role of Carnot battery and heat pump technologies in future low-carbon energy systems.

2. Methodology

2.1. HEAT SAND

This study is part of the ongoing Korea Institute of Energy Research (KIER)'s research project HEAT SAND (High tEmperature sAnd Thermal storage with Shielded Al-Si alloy fiN Design), which aims to develop a core thermal energy storage technology utilizing sand and Al–Si for high-temperature energy storage applications (Fig. 2). The HEAT SAND project focuses on designing and optimizing a thermal storage system capable of operating at a storage temperature of 577 °C and maintaining steam generation conditions of 538 ± 25 °C and 246 bar, suitable for integration with coal-fired power plant retrofits into Carnot battery systems. Key technical features of the HEAT SAND system include:

- Development of surface-reinforcement techniques for the Al–Si PCM to enhance thermal and mechanical stability under repeated melting–solidification cycles
- Application of fin-type Al–Si structures within the sand matrix to improve heat transfer performance and achieve uniform temperature distribution throughout the storage medium

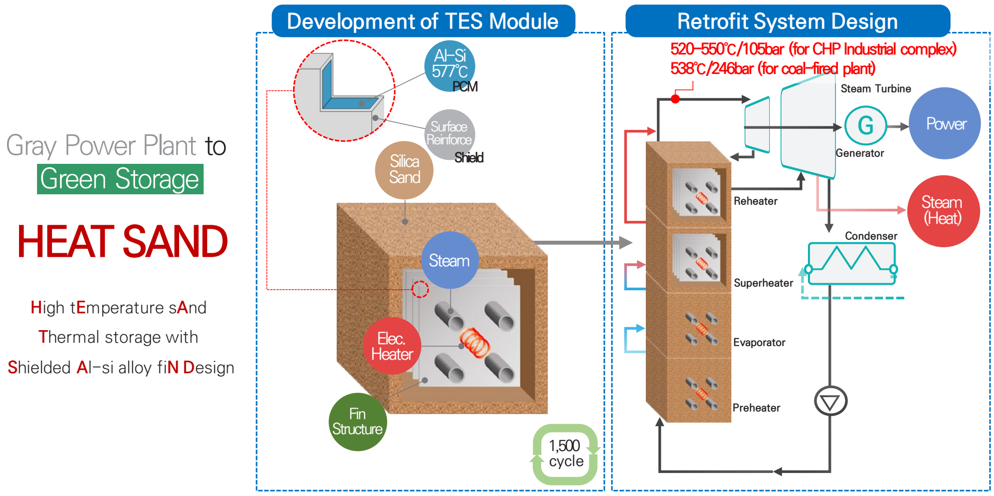

Figure 2. Conceptual Schematic of the HEAT SAND System.

These design approaches aim to establish a robust and scalable thermal energy storage system that meets the operational requirements of high temperature steam generation in Carnot battery applications. Based on this system design, subsequent techno-economic evaluations (Including the LCOH and LCOS) were conducted.

2.2. Levelized Cost of Heat and Storage

The Levelized Cost of Heat (LCOH) and Levelized Cost of Storage (LCOS) are generally composed of three major components: (1) the capital expenditures (CAPEX) required for system construction, (2) the operating expenditures (OPEX) associated with system operation and maintenance, and (3) the total thermal or electric energy yield, which represents the total amount of thermal or electrical energy produced by the system over its lifetime.

Using these three components, the basic formulation for calculating LCOH and LCOS is expressed as shown in Eq. (1) and (2), where *n* denotes the system lifetime. In this study, both LCOH and LCOS were calculated based on Eq. (1) and (2). The total thermal energy yield was converted into the equivalent amount of produced steam to determine the cost of steam production in units of [KRW/ton], while the electric energy yield was used to evaluate the cost of electricity generation through storage in units of [KRW/kWh].

$$LCOH = \frac{CAPEX + \sum_{i=1}^{n} OPEX_i}{\sum_{i=1}^{n} Thermal\ energy\ yield_i}\ [\$/ton] \tag{1}$$

$$LCOS = \frac{CAPEX + \sum_{i=1}^{n} OPEX_i}{\sum_{i=1}^{n} Electric\ energy\ yield_i}\ [\$/kWh] \tag{2}$$

In large-scale energy storage systems, CAPEX accounts for a significant portion of the total cost. The cost of fuel or electricity used for thermal energy storage is typically included in OPEX [6]; however, it can also be treated as a separate factor [7] depending on the calculation approach. In either case, the system's overall energy conversion efficiency is reflected in the cost evaluation.

2.3. System Configuration for LCOH Analysis

Fig. 3 illustrates the system configurations considered for the LCOH analysis in this study, including a heat pump–based steam generation system, a Carnot battery charged using a heat pump, and a Carnot battery charged using an electric heater. All systems are designed to produce industrial steam under comparable temperature and pressure conditions.

In the heat pump system, electricity is directly converted into thermal energy through the heat pump, and the generated heat is supplied to produce industrial steam without intermediate energy storage.

In contrast, the Carnot battery systems decouple electricity consumption from steam production by storing thermal energy. In the heat pump–assisted Carnot battery configuration, electricity is converted into high-temperature heat via a heat pump and stored in the thermal energy storage system. In the electric heater–based Carnot battery configuration, electricity is directly converted into heat using an electric heater before being stored. In both cases, the stored thermal energy is later used to generate industrial steam.

These configurations allow a comparative evaluation of LCOH with respect to electricity price, energy conversion pathways, and the presence or absence of thermal energy storage.

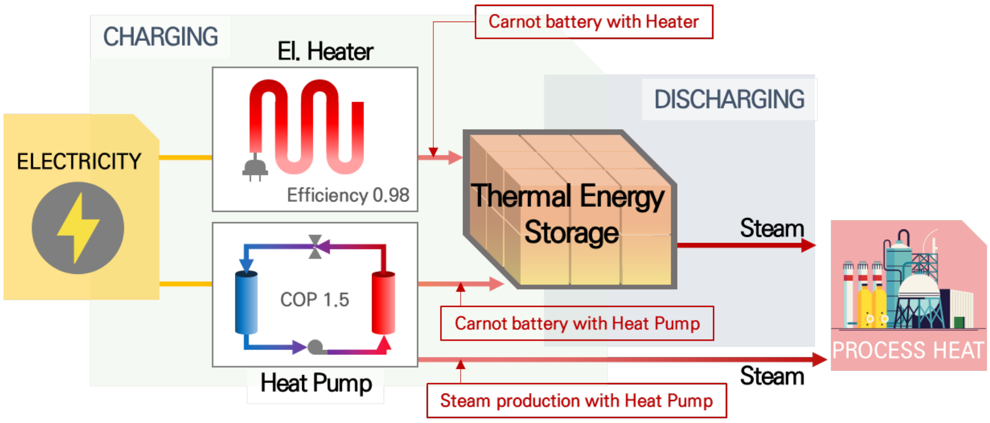

Figure 3. System Configurations for LCOH Analysis: Heat Pump, Carnot Battery with Heat Pump, and with Electric Heater

3. Results and Discussion

3.1. Levelized Cost of Heat for Heat Pump and Carnot Battery

The LCOH for industrial steam production using the Carnot battery and heat pump was calculated based on the methodology proposed by Gilbert et al. [7]. In this approach, the cost of fuel (electricity) used for thermal energy generation is separated from the general OPEX and treated as an independent component in the LCOH formulation. The resulting LCOH values obtained from this study are presented in Fig. 4.

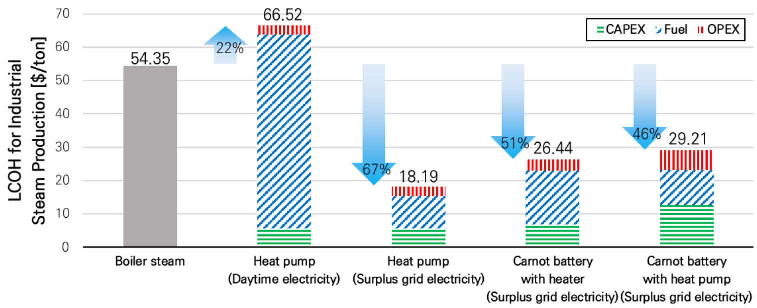

Figure 4. Comparison of LCOH for Industrial Steam Production Using Heat Pump and Carnot Battery

For the economic assessment, this study applied electricity prices representative of South Korea—daytime electricity at approximately 153.7 KRW (≈0.106 USD/kWh) and nighttime electricity at approximately 71.9 KRW (≈0.050 USD/kWh)—along with the surplus grid electricity price of 0.02 USD/kWh reported in the DLR study from Germany [6].

For the heat pump case, the LCOH calculated using daytime electricity exceeds the current industrial steam production cost in Korea (approximately 78,801 KRW/ton ≈ 54.35 USD/ton). However, because fuel (electricity) constitutes a significant portion of the LCOH, using low-cost surplus grid electricity drastically improves economic performance. When applying the surplus grid price, the LCOH for heat-pump-based steam production is reduced by nearly 70% compared to the current market steam price.

Unlike heat pumps, which can benefit from low-cost surplus grid electricity only when it is directly available, the Carnot battery can store electricity during low-price periods and utilize it later for steam production. This operational flexibility allows the Carnot battery to access inexpensive surplus electricity over a wider range of operating hours. As a result, steam production using the Carnot battery achieves an LCOH approximately 50% lower than the current market steam price, regardless of whether an electric heater or a heat pump is used for charging.

3.2. Retrofit of Coal-Fired Power Plants and Combined Heat and Power Plants into Carnot Battery Systems

The LCOS was evaluated for the case in which an existing coal-fired power plant is retrofitted into a Carnot battery system with heater. The results are presented in Fig. 5. When retrofitting a coal-fired plant, major power generation components such as the steam turbine can be reused without additional installation. This provides a substantial economic advantage by significantly reducing CAPEX requirements. Accordingly, in the LCOS calculation, the turbine and associated power-generation equipment were excluded from CAPEX and considered only in OPEX.

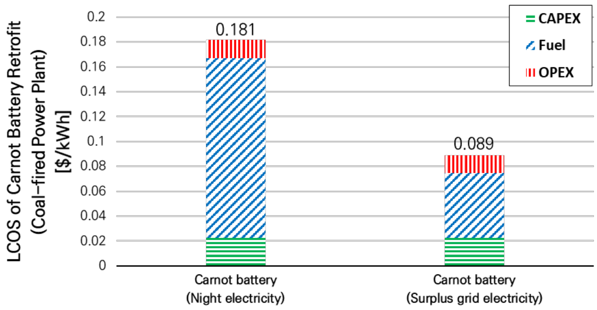

Figure 5. LCOS of Coal-Fired Power Plant Retrofit into a Carnot Battery

When low-cost surplus grid electricity is used for charging, the LCOS is calculated to be 0.089 USD/kWh, which is approximately half the value obtained when using nighttime electricity prices.

Subsequently, the LCOH and LCOS were analyzed for the case of retrofitting a Combined Heat and Power (CHP) plant into a Carnot battery system, as shown in Fig. 6. For CHP retrofits, CAPEX, OPEX, and fuel costs were allocated according to the target steam-to-electricity production ratio. Similar to the coal-fired power plant case, the turbine was excluded from CAPEX; however, because the turbine is used exclusively for electricity production, the full turbine-related OPEX was allocated solely to the LCOS calculation.

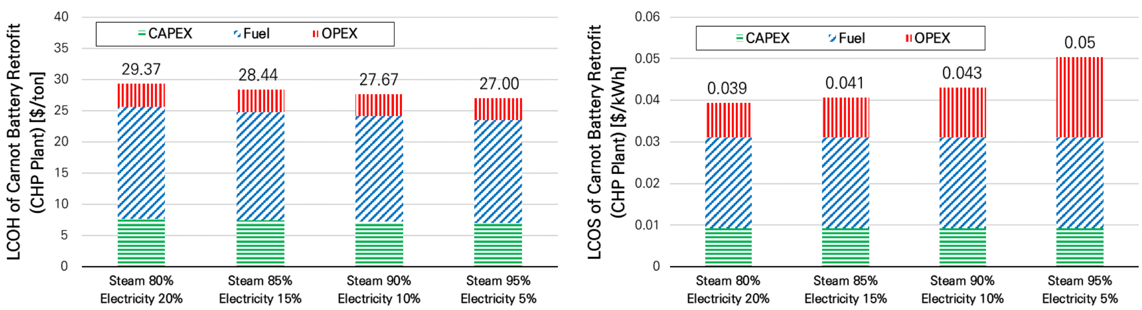

Figure 6. LCOH and LCOS of Combined Heat and Power (CHP) Plant Retrofit into a Carnot Battery

The enthalpy loss associated with recovering exhaust steam after electricity generation was assumed to be approximately 10%, which is a conservative value consistent with reported heat/enthalpy penalties in backpressure steam-turbine applications [8-9]. Therefore, as the share of electricity production increases, a larger portion of steam passes through the turbine, resulting in higher enthalpy losses and consequently higher LCOH values.

In contrast, the OPEX associated with the turbine remains constant in the LCOS calculation. Thus, even when the electricity share decreases, the turbine OPEX does not decrease proportionally, leading to an increase in LCOS at lower electricity production ratios.

However, unlike coal-fired power plants, CHP plants are able to utilize the turbine exhaust steam rather than discarding it. As a result, only the fraction of CAPEX, OPEX, and fuel corresponding to the electricity production share is counted toward LCOS. This characteristic enables CHP retrofits to achieve significantly lower LCOS values compared to coal-fired plant retrofits

4. Conclusion

This study evaluated the techno-economic feasibility of industrial steam production and electricity storage using Carnot battery and heat pump systems, based on the high-temperature sand–AlSi thermal storage technology under development in the HEAT SAND project. LCOH analysis showed that heat-pump-based steam production is economical only when low-cost surplus grid electricity is directly available, whereas the Carnot battery can store low-cost electricity and utilize it for steam production beyond the periods of direct availability, resulting in an LCOH approximately 50% lower than the current industrial steam price.

For plant retrofit scenarios, converting coal-fired power plants into Carnot battery systems significantly reduces LCOS by reusing existing turbine equipment. CHP plant retrofits demonstrated even greater economic benefits, as turbine exhaust steam can be recovered and only the electricity-related portion of costs contributes to LCOS. As a result, CHP retrofits achieved notably lower LCOS values compared to coal-plant retrofits.

Overall, the results indicate that Carnot battery systems offer strong economic potential for both steam production and long-duration electricity storage, highlighting their competitiveness in future electrified and decarbonized energy systems.

Acknowledgements

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