

Modeling the Impact of Mid-Term Storage on Electricity Markets: Insights from Carnot Battery Integration

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Abstract—This study analyzes mid-term storage technologies in the German market using the agent-based electricity market model PowerACE to assess their market impact and economics. An energy system pathway is defined, and Carnot batteries with three different round-trip efficiencies (RTE) and varying energy-to-power (E2P) ratios are investigated. Results indicate that, under the given market scenario, higher E2P ratios increase the impact on the market by reducing market prices, imports to Germany, and volatile renewable energies curtailment. Furthermore, longer discharge durations lead to lower profitable specific costs per energy unit, as the additional revenue does not fully compensate for the increased costs for energy capacity. This study provides a foundation for the economic assessment of technical design parameters as well as the impact of mid-term storage on market dynamics.

Index Terms—Electricity market model, Agent-based modeling, Energy storage, Carnot battery

I. INTRODUCTION AND STATE OF THE ART

The growing share of volatile renewable energy sources (vRES) and the decline in conventional power generation increase the need for storage systems to ensure the stability of the electricity supply. Longer periods of low renewable energy generation, which can last days or even weeks, cannot be adequately bridged by short-term storage solutions, such as lithium-ion batteries. In this context, mid-term¹ storage systems – which can discharge over periods of eight hours to weeks – offer a reliable way of bridging these gaps. Lithium-ion batteries established themselves as the main technology for short-term storage but face challenges from an economic point of view when it comes to mid- and long-term energy storage. Moreover, they pose risks related to availability due to the limited annual production of lithium [1]. The cost structure of lithium-ion batteries differs from that of other storage

technologies, as power and energy cannot easily be scaled independently in a cost-effective manner, whereas mid-term storage technologies, such as compressed air energy storage (CAES), pumped hydro storage (PHS) or the Carnot battery, offer cost-effective scalability, making them a promising alternative [2], [3]. However, the technical and economic maturity of mid-term storage systems has been limited – or, in the case of PHS, there is only a limited potential for new sites. It is therefore difficult to assess the impact of these storages on the electricity market, as this depends both on the techno-economic parameters of these storage systems used and on the storage capacity in the electricity market.

Several studies examine the integration of mid-term storage technologies into the energy system. Lund et al. [4] evaluates the role of CAES in sustainable energy systems. They conclude that in energy systems with high wind power and combined heat and power shares, price fluctuations on the spot market alone do not justify CAES system investments. Dowling et al. [5] analyzed 100% reliable electricity systems with wind and solar generation, supported by storage systems with durations exceeding 10 hours and battery storage. The results indicate that reducing costs and deploying storage systems with extended durations at scale would lower system costs in reliable wind and solar power systems far more than equivalent battery cost reductions. From a market perspective, Sorknæs et al. [6] conclude that the potential economic benefit of Carnot batteries in a renewable system could be as high as 60.5 – 66.2 €/MWh_{el} discharged while Nitsch et al. [7] conclude that Carnot battery operators can achieve a positive net present value, driven by system design, their bidding strategy, and market power.

In this paper, we investigate the impact of different mid-term storages represented by Carnot battery configurations on the market. By assessing the profitability of a configuration within an agent-based electricity market model, we extend the

¹This paper examines short- to mid-term storage options. Typical long-term storage facilities, such as reservoirs for hydrogen or other gaseous energy carriers or large-scale

hydro reservoirs, are not considered, as their main purpose is primarily long-term energy balancing rather than short- to mid-term storage.

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literature on competitive storage investment options along an energy system path. In particular, we examine the implications of deploying mid-term storage technologies with longer discharge durations and lower efficiencies instead of short-term lithium-ion batteries to gain insights into the profitability of mid-term storage investment options and their technical design parameters. The paper is organized as follows: Section II outlines the electricity market model and the calculation of the storage profitability. Section III presents the case study. Section IV discusses the results and findings. Finally, Section V provides the conclusion and critical reflections.

II. METHODOLOGY

A. Agent-based Electricity Market Model PowerACE

The established agent-based model PowerACE [8]-[10] is used to examine the impact of mid-term storage technologies on the electricity market and to evaluate different mid-term storage configurations. PowerACE simulates a day-ahead market up to 2050 with hourly resolution, considering various market areas. It models the planning and simulation of the hourly operation of power plants, focusing on aspects such as demand, renewable energy generation, resource availability, and prescribed operating conditions. In the model, renewable energies and demand are exogenous parameters, while each conventional generation unit and storage facility acts as an independent agent. Each agent pursues individual objectives and makes decisions based on its own interests and capabilities, without centralized system planning. This allows each generation unit to develop its own optimal strategy, resulting in a decentralized decision-making process. Model outputs include, among other results, the power plant dispatch, imports and exports, vRES curtailment and electricity prices. A good general overview of the model can be found in Fraunholz [8] and Zimmermann [9].

B. Assessment of Electricity Storage Economics

The storage technologies modeled in PowerACE are marketed as individual agents. PowerACE includes a price forecast that is used by the storage units as a basis for price-based optimization. The optimization aims to maximize revenues while considering storage constraints. The market outcome can be used to determine the total revenue and the average revenue per unit of energy sold. As the investigated mid-term storages are added to the system without consideration of investment costs, the approach to determining profitability takes an inverse method. By calculating the revenues achieved, the maximum costs the storage system can incur while remaining profitable for an investor are determined. Dividing the total revenues by the total electrical energy delivered over the storage system's lifetime provides the revenue per unit of energy sold. To remain profitable, the cost per unit of energy delivered must not exceed the revenues per unit of energy sold. This cost is typically described by the Levelized Cost of Storage (LCOS). It is calculated using the following equation:

$$LCOS = \frac{CAPEX + \sum_{t=1}^n \frac{OPEX_t}{(1+i)^t}}{\sum_{t=1}^n \frac{W_{out,t}}{(1+i)^t}}. \quad (1)$$

The numerator represents the sum of the capital expenditure $CAPEX$ and the operational expenditures $OPEX_t$ incurred by the storage system at each time t over its lifetime n , discounted by the interest rate i . Similarly, the denominator represents the annual energy output $W_{out,t}$, also discounted over the same period. The LCOS is commonly used in the literature to compare the costs of various storage systems. By applying this approach, it becomes possible to determine the maximum allowable LCOS for a specific storage system, allowing a direct comparison with the performance of investigated storage technologies. Note that the LCOS typically depends on the assumed number of storage cycles and average electricity price. In this study, the cycles and electricity prices are derived from the market outcomes.

C. Determination of Budget Constraints for Independent Storage Sizing

For storage technologies where the storage volume (MWh) can be scaled independently of the power (MW), the total revenues mentioned in Subsection B can be used to determine the maximum allowable investment costs for energy capacity and power. A reduction in energy costs allows for higher costs in power, and vice versa. According to (2), the result forms a function that represents the trade-off between energy and power investment costs as a budget constraint.

$$c_E = \frac{\left(\frac{p_{total}}{1+r_{OPEX}}\right) - c_P \cdot P}{E} \quad (2)$$

The specific investment costs for energy c_E are defined as a function of the specific investment costs for power c_P . The total revenues p_{total} that a storage system can generate over its lifetime, the operational expenditures r_{OPEX} as rate of total investment costs, the total power P , and the total storage energy capacity E are considered as parameters of the storage technology.

III. CASE STUDY ON CARNOT BATTERIES

A case study is conducted to evaluate the profitability of different mid-term storage configurations and analyze their impact on electricity markets. This was investigated by modeling various Carnot battery configurations in PowerACE, using their parameters to represent mid-term storage technologies. The modeling approach and methodology can also be applied to the parameters of other storage technologies. Carnot batteries convert electrical energy into thermal energy. They store this energy in a thermal energy storage system. When needed, the stored heat is converted back into electricity. The design of Carnot batteries is highly flexible. The three main components – electricity to thermal energy conversion, thermal energy storage, and thermal energy to electricity conversion – can be scaled independently. Various technologies can be used for each component. This choice of

technology affects the round-trip efficiency (RTE) of the configuration. The configurations and their references used in this study are listed in Table 1.

TABLE I. CARNOT BATTERY CONFIGURATIONS

	Round-Trip Efficiency	Reference
Electrical heater + Rankine Cycle	44.5%	[11]
Heat pump + Joule-Brayton cycle	53%	[12]
Heat pump + ORC	72.5%	[13]

Three different configurations are considered to provide variability: an electrical heater system with a Rankine cycle, a heat pump and Joule-Brayton cycle, and a heat pump with an organic Rankine cycle (ORC). The configurations are designed with different energy-to-power (E2P) ratios representing the discharge duration at a specified power level. The considered E2P ratios – 8, 24, 72, and 168 hours – span a range of mid-term storage capacities. Charge and discharge power are assumed to be equal, and RTE is modeled as input efficiency. For an E2P ratio of 8 hours and a power of 1 MW_{el}, the electrical capacity is 8 MWh_{el}, allowing continuous discharge at full power for 8 hours. Self-discharge of the storages and variable operating costs are neglected as their impact on the economics of the storage is minor compared to other factors. The lifetime is assumed to be 20 years. Based on [12], a discount rate of 5% and fixed operating costs amounting to 1% of the investment costs are assumed. These configurations are integrated exogenously in PowerACE. A simulation is performed for each configuration paired with each E2P ratio. An additional simulation without any Carnot battery configuration serves as a benchmark.

The PowerACE simulations were carried out with 15 market areas. The study examines the interdependencies of the European electricity market with a focus on Germany, using simulations covering the years 2030 to 2040. It is assumed that Carnot batteries will enter the market in large numbers later, due to their low Technology Readiness Level (TRL). After 2040, the last simulation year was applied to all subsequent years. The energy system pathway was modeled using the National Trends scenario from the ENTSO-E Ten-Year Network Development Plan (TYNDP) draft of May 2024 [14]. The years 2031 to 2039 were interpolated based on the reference years 2030 and 2040. The National Trends scenario does not include Carnot batteries. Therefore, in all simulations except for the benchmark run, 10 GW of utility-scale battery storage (lithium-ion battery) is replaced with 10 GW of the corresponding Carnot battery configuration. Table 2 presents the used capacities for the German market area. Fuel prices, CO₂ prices, and demand are also based on the National Trends+ scenario. Generation profiles for renewable energies are taken from the Pan-European wind and solar generation time series from the Technical University of Denmark in

cooperation with ENTSO-E [15]. The underlying weather year is 2009.

TABLE II. CAPACITIES OF THE ENERGY SYSTEM PATHWAY [14]

	2030	2040
Peak-load power plants (natural gas and hydrogen)	34.5 GW	32.6 GW
Baseload power plants (run-of-river, hard coal and lignite)	3.9 GW	3.9 GW
Wind	145.1 GW	223.6 GW
Solar	215 GW	365.9 GW
Pumped-hydro storage	9.2 GW	10.7 GW
Lithium-ion storage (4 hours)	3.2 GW	99.8 GW
Carnot battery	0 GW	10 GW
Others	22.8 GW	9.1 GW

IV. RESULTS

A. Impact on electricity market

Figure 1 shows how the different E2P ratios and the RTE affect the market. The graph shows the change in the market price, vRES curtailment, imports and exports, and the dispatch of peak-load power plants compared to the benchmark simulation. The use of larger E2P ratios has a significant impact on the market. Storage systems with a high E2P ratio facilitate the shifting of vRES generation to hours with high residual loads, during periods when peak-load power plants must intervene. The production of these plants is curtailed, which subsequently lowers market prices. Additionally, the longer charging time results in a better integration of vRES generation rather than curtailment. For the same reason, an increase in the RTE also leads to lower market prices, while it can be seen that there is a trend in less curtailment with higher RTE. A lower RTE requires more consecutive hours of low prices to charge the same amount as with a high RTE. As a result, the storage utilizes less energy from vRES, leading to more curtailment. In addition, the deployment of mid-term storage technologies induces cannibalization effects on lithium-ion batteries. The extent of these effects depends on the RTE of the Carnot battery and the E2P ratio. Lower RTE at relatively low E2P ratios results in reduced competition with lithium-ion batteries, and in the case of an RTE of 44.5%, they even have a positive impact on revenues. However, as the E2P ratio increases, the cannibalization effects become more apparent. With further increases in the E2P ratio, these effects diminish again, as the competition between the two storage technologies decreases.

B. Evaluation of Electricity Storage Economics

Figure 2 illustrates the average capacity factor for discharge cycles for each applied Carnot battery configuration and lithium-ion batteries. The capacity factor for discharge cycles

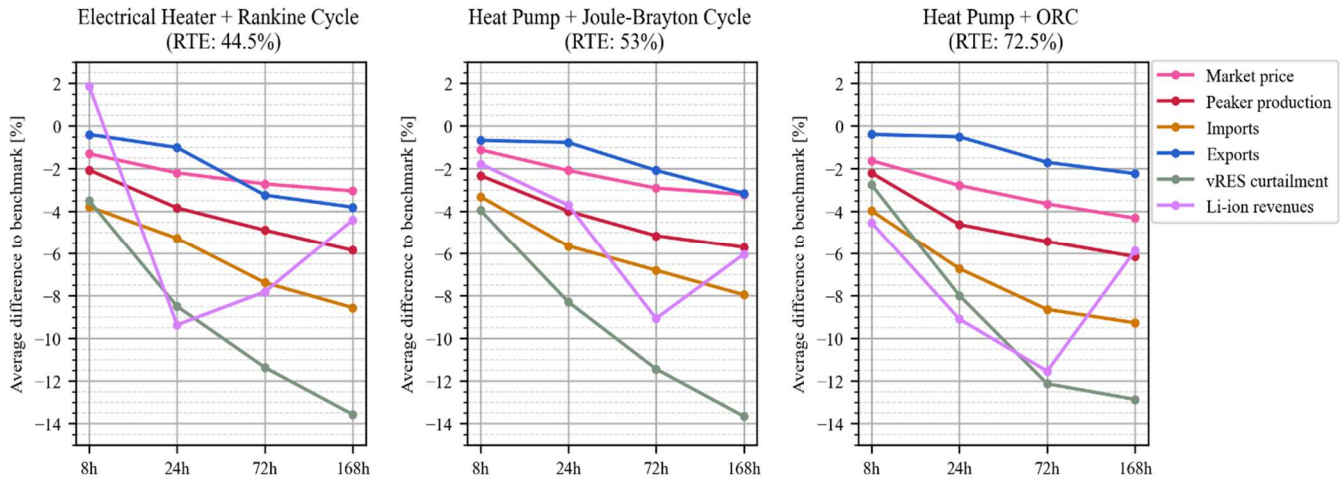


Figure 1. Average difference of market price, peak-load power plant production, imports, exports, curtailment of vRES and lithium-ion battery revenues for each applied configuration in percent compared to the benchmark simulation

is defined as the ratio of discharge cycles to the maximum possible discharge cycles per year. The results indicate that the different Carnot battery configurations do not significantly affect the dispatch pattern of lithium-ion batteries. As discussed in the previous section, a higher E2P ratio increases the number of possible discharge hours, thereby also leading to more discharge cycles, as it allows for greater utilization of vRES. In addition, the RTE influences the capacity factor: a higher RTE allows for purchasing more energy at lower prices, which in turn enables selling at lower prices. This use of smaller price spreads consequently leads to an overall increase in discharge cycles.

Fig. 3 illustrates the trade-off between maximum specific energy and power investment costs as budget constraints across configurations. By fixing the costs per unit of power, the figure illustrates the maximum allowable costs per unit of energy for the configuration to achieve a net present value

equal to zero. It can be observed that budget constraints become less restrictive for higher RTEs, leading to higher revenues. Additionally, for the same reason, a higher E2P ratio allows for higher specific investment costs per MW_{el} , as the total installed capacity of Carnot batteries is assumed to remain constant across different simulations. However, the maximum specific investment costs per MWh_{el} decrease with increasing E2P ratios, as a significantly larger storage capacity must be deployed to achieve the same level of revenue. Comparison with study [16] indicates that the 8h and 24h configurations fall within a range of sufficiently low specific investment costs to be profitable, while the 72h and 168h configurations tend to fall outside this range.

Table 3 shows the maximum LCOS at which the corresponding configuration would be profitable. It can be observed that the maximum allowable LCOS increases with higher E2P ratios, while it decreases with higher RTE.

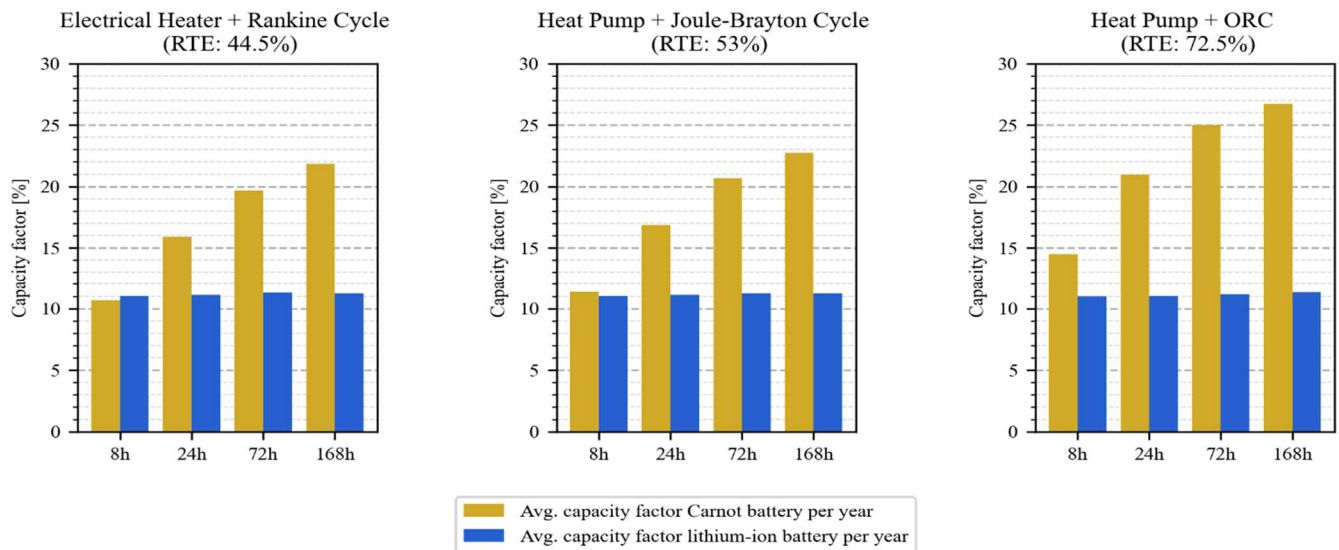


Figure 2. Average capacity factor for discharge cycles for each applied Carnot battery configuration and for lithium-ion batteries. The capacity factor for discharge cycles is defined as the ratio of discharge hours to the maximum possible discharge hours per year.

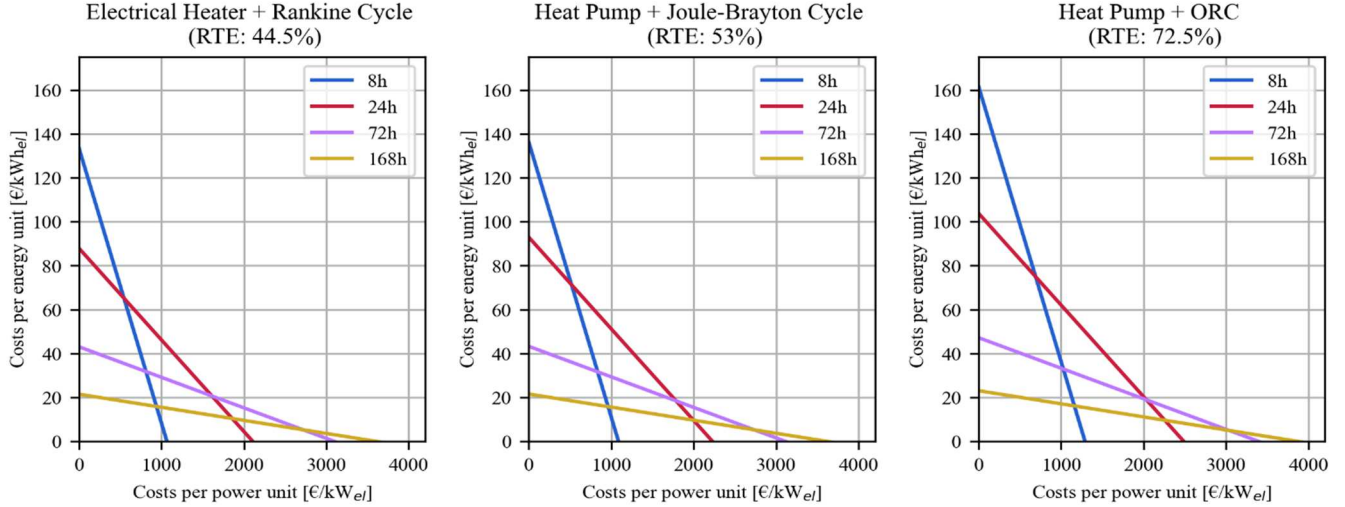


Figure 3. Trade-off for maximum cost limits as budget constraints for investment costs per energy unit [€/kWh_{el}] and power unit [€/kW_{el}] for each applied configuration

However, Figure 3 indicates that revenues increase with both higher E2P ratios and higher RTE. The decline in the maximum allowable LCOS can be attributed to the fact that a higher number of possible cycles enables the utilization of smaller electricity price spreads, thereby reducing the revenue per discharged MWh_{el}. To ensure a meaningful comparison of LCOS values, the same number of cycles must be considered so that the discharged energy is proportionally allocated to the incurred costs. Study [6] compares LCOS across various Carnot battery system studies. Due to variations in scale and technology, a wide range is observed. The LCOS determined in these studies tend to exceed the benchmarks from Table 3 and would not be profitable under the given scenario, particularly considering the number of cycles.

TABLE III. MAXIMUM PROFITABLE LCOS FOR EACH CONFIGURATION

	max. LCOS [€/MWh _{el}]		
	RTE: 44.5%	RTE: 53%	RTE: 72.5
8h	142.35	142.08	129.44
24h	181.97	180.91	162.43
72h	200.76	190.36	174.11
168h	204.71	196.22	181.13

V. CONCLUSION

This study models and analyzes mid-term storage technologies in the German market area using an agent-based electricity market model to evaluate their market impact and profitability. Moreover, the results offer a foundation that facilitates the economic assessment of technical design parameters.

From a market perspective, the key findings indicate that an extended discharge duration of mid-term storage technologies

can lead to lower market prices and reduced curtailment, despite their lower round-trip efficiency. Simultaneously, mid-term storage technologies can induce cannibalization effects on short-term storage technologies such as lithium-ion batteries. However, as the discharge duration of mid-term storage increases, competition with short-term storage technologies decreases. From a profitability perspective, the results indicate that revenues increase with both longer discharge durations and higher round-trip efficiency. This is accompanied by a greater number of possible discharge cycles. Consequently, the revenue per discharged MWh_{el} decreases. Furthermore, the findings suggest that longer discharge durations lead to lower profitable specific costs per MWh_{el}, as the additional revenue does not fully compensate for the increased costs for the high energy capacity. As a result, the specific investment costs for configurations with shorter discharge durations, as reported in the literature, fall within the maximum profitable range determined in this simulation. However, this is not the case for configurations with longer discharge durations.

While the study provides valuable insights, several limitations should be noted. The analysis is based on specific market condition and scenario, which may not fully capture future developments. Additionally, storage technologies are modeled in a simplified manner and simplified assumptions are made to evaluate their profitability. Each simulation in this study considers only a single configuration, without accounting for interactions between multiple configurations. Furthermore, profitability is influenced by the chosen trading strategy. Future research should explore various scenarios as well as multiple configurations and their interactions. This would enable a deeper understanding of shifts in the most profitable configuration and its market implications. Additionally, future studies should investigate the impact of varying input and output capacities for individual storage systems, as this could provide significant advantages in systems with high shares of volatile renewable energy sources.

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