Are Carnot Batteries an Alternative When Repurposing Coal Power Plants in Europe?

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Abstract. As Europe transitions away from coal-fired power plants, there is indecision regarding the fate of the retiring sites. This paper tests the feasibility of an alternative to consider: Carnot Batteries. Refurbishing existing power plants has several advantages. Components can be put to a new purpose. The locations are connected to the electricity and district-heating grids. Both reduce the costs of a Carnot Battery. The literature regarding retrofit operating power plants with thermal energy storage focuses on improving an existing power plant. This paper determines the technoeconomic feasibility of replacing the boiler as the source of heat with a direct heater and thermal energy storage. Carnot Batteries can contribute to mitigating the variability of renewable energy and increase its proportion of the energy production mix. The first step is a deterministic analysis of dispatch and then genetic optimization for the sizing. The optimization relies on open-source software for replicability and further development. The results point to feasible arrangements for the European electricity market if the assumptions regarding the possibility to reutilize the power block is true. For the electricity markets analyzed in detail here, it is possible to find a solution with a market competitive Internal Rate of Return, positive Net Present Value, and comparable Levelized Costs of Storage, particularly for the Romanian electricity market. Analysis of technical parameters highlights the importance of round-trip efficiency and shows a possible reduction in carbon emissions. This broad analysis argues for further investigating Carnot Batteries as an alternative when determining how a retired coal-fired power plant can be repurposed.

Keywords: Coal-fired Power Plants · Carnot Battery · Techno-economic Analysis · Dispatch and Sizing Optimization · Genetic Algorithm

1 Introduction

A transition away from fossil fuels, particularly coal-fired, is underway in Europe. 207 coal-fired power plants are announced to retire with a total of 63 GW of capacity between 2022 and 2048 [1]. This accounts for 6% of Europe's installed capacity as of 2020. There is now a window of opportunity to address what should happen with the infrastructure and assets of the closing power plants. This paper does an exploratory study of one possibility within Europe Carnot batteries. Power-to-heat-to-power systems, or Carnot batteries,

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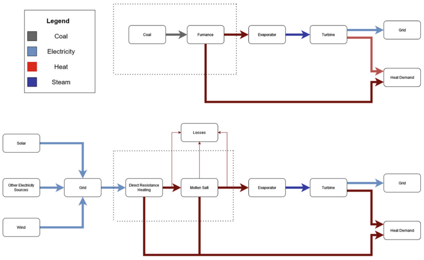

Fig. 1. Diagram of the analyzed solution.

take electricity from the grid, convert it to heat, store the heat, and then convert the heat back to electricity. There several are barriers to the implementation of a 100% renewable Europe [2], but this paper will focus on the synergy between the two problems. The first is the transition from fossil to renewable whilst supporting the grid and energy demands. New forms of power production need to be installed and others taken away while lives and economies which depend on electricity cannot be disrupted. The second is dealing with the variability of renewable energy. This includes windless nights when there is little solar or wind power, quick changes which are hard to predict, and a mismatch between the availability and demand of renewable resources. The principal solution discussed here is to store excess power by repurposing closing coal-fired power plants into thermal batteries.

Storage can fulfill different goals most notably here price regulation [3, 4]. The price of electricity in each electricity market can be regarded as a balance between production and demand. The price signals however function on a slower scale, often hourly and with a 24-h delay [5, 6].

As plans for mitigation of climate change are being implemented, fossil-based power plants are closing, and renewable energy production has been growing and is forecasted to continue [2, 7]. Fossil energy is dispatchable whilst the wind and solar sources are variable requiring storage [8]. However, storage options are either geographically bound (most notably pumped hydropower) or costly [3, 9]. The utilization of components can reduce the costs of Carnot Batteries. Furthermore, investments made into fossil-based energy sources become stranded assets if no action is taken. Thermal batteries can be applied anywhere, hold and provide power for long timescales (hours-days), and do not degrade over their long lifetime [10]. Reutilizing the site of retiring power plants could reduce the costs, particularly of the power block. There is extensive literature regarding the possibility to include thermal energy storage in either existing coal-fired powers or new concentrated solar power [10–12]. The implications for the component-wise thermodynamics [13], the dispatching [14–18], and the economics [19, 20] of coal-fired supported by thermal energy storage are promising. However, the situation in Europe is the retirement of coal-fired power plants. This implies that the coal-fired boiler is no longer in use but rather than improved.

The proposed solution as Fig. 1 is to substitute the heat source of coal-fired power plants which are planned or announced to retire with a direct electric heater and molten salt system. The boiler of the coal-fire plant is removed or circumvented; instead, a direct

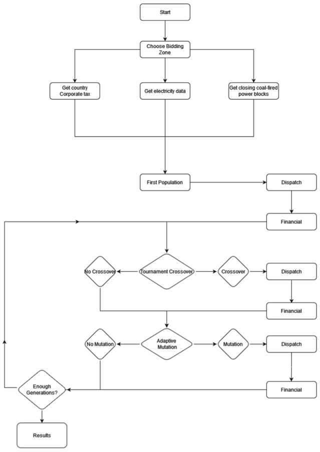

Fig. 2. Flowchart of the optimization method.

electric heater and the molten salt system are built. The power block (i.e. turbine) and connection to the electricity and heat grid can be re-utilized. There are losses in the energy conversion and storage of the system This would allow the low emission, low price energy of renewable electricity to be stored and dispatch when it is needed. The concept is not entirely novel [21, 22]. There are even component designs for radiative-based components which could be applied [23] and efforts to commercialize the process [24].

The research aims to test whether a Carnot Battery can be feasibility installed in each electricity market. If running the test arrangements proves to be financially attractive, it strengthens the argument that it is a plausible solution for addressing the potential issues of a transition from fossil fuels. If several configurations are feasible, Carnot Batteries should be considered as an option when determining the fate of retiring coal-fired power plants. Conversely, if by testing many arrangements, none are economically sustainable, it weakens the argument for their implementation.

The scope of this paper is defined around Europe and the day-ahead markets. There are several limitations to this model. The principal one surrounds the linear optimization scheme which simplifies the complex thermodynamics processes into a thermal loss and two static efficiency factors. Sensitivity analysis shows that results are sensitive to efficiency but adapting would require non-linear optimizations in the dispatch stage. Even with the simplifications made, the model takes a long time to run. Further limitations include the difficulty to validate the economics since a transition from coal-fired to Carnot battery has not been built and the assumption that the model knows the exact prices of the electricity one week ahead of time. Predicting electricity prices, particularly spikes, is a complex problem [25].

2 Method

Three design variables were chosen to model the Carnot battery: the direct electric heater, the molten salt storage, and the power block. The direct electric heater determines the rate of conversion from electricity to thermal energy. The maximum storage capacity, finally the power block is to the turbine from being repurposed and determines the rate at which the thermal energy can be converted back to electricity (Fig. 2).

There are two steps to optimizing the configuration of the Carnot Battery, dispatch and sizing. To determine whether the solution is technically and economically feasible the dispatch is optimized with a determined linear optimization to establish the extent to which a power source is profitable in a year. This information is then applied to a non-linear genetic algorithm to determine which design factors are best fitted for a given electricity market.

The dispatching problem refers to the systematic optimization of when and how much a certain power unit should produce electricity. In the context of storage, this includes the extent to which it should consume energy to store power. In this analysis, the dispatch will be optimized around the economic factors to keep the system cost-effective, an important indicator for investors [26].

Using the results of the dispatch in combination with assumptions of the cost of the components and how these costs scale, it is possible to ascertain whether and to what extent a configuration would be profitable. This process is non-linear requiring another optimization method. A genetic algorithm was applied to find feasible design variables.

3 Modelling

With the method outlined, the best way to achieve it so systematically test with the support of established programming libraries. The model was written in Pyomo, an open-sourced high-level language [27, 28], and solved with COIN-OR Branch-and-Cut [29] and PYGAD [30].

The objective function, Eq. (1), seeks to reduce the costs of supplying a given heating demand. If the heating demand is set to zero, the battery seeks to profit by buying when the price and selling when it is high. If that cost is negative, the battery can provide a yearly income. Whether this income is sufficiently high to justify the investment in the battery is tested in the next stage. The model is set to run for a full year, thus capturing the different seasons and holidays. Running the 8760 h simultaneously is too computationally expensive, so the model breaks the year into weeks and then concatenates the weeks. This means that the model is suboptimal but reflects the difficulties in long-term price predictions and the charge-discharge cycle of the battery.

$$\begin{aligned} Objective = \sum_{hour=1}^{8760} (&Electricity_{bought}[hour] * ElectricityPrice[hour] \\ &- Electricity_{sold}[hour] * ElectricityPrice[hour]) \end{aligned} \tag{1}$$

Table 1 demonstrates the constraints applied to the battery model. These can be classified as maxima and minima or flexibility issues. The maximum or minimum are connected to the design property. For instance, the power block cannot operate below 20% of its nameplate capacity. Flexibility refers to the commitments to a certain number of hours that the system makes when powering on or off and ramping up or down. These

Table 1. Assumptions for technical parameters

Parameter	Value
Efficiency Power-to-Heat	80%
Efficiency Heat-to-Power	80%
Minimum Charge Power	10%
Minimum Discharge	20%
Minimum Commit On/Off Direct Electric Heater	4/3 h
Minimum Commit On/Off Power Block	5/5 h
Maximum Ramp Up/Down Direct Heater and Power Block	50/50%/hour
Minimum state of Charge	10%
Maximum state of Charge	90%
Thermal losses	$0.05^{1/24}$% of the state of charge/hour

Table 2. Assumptions and inputs for the financial sizing optimization.

Components	Costs	Unit
Direct Electric Heater	500,000	2021€/10 MW
Tanks	42,888,000	2012$/1,745 MW
Piping	1,418,000	
Foundation	520,000	
Pumps and Heat exchangers	29,766,000	
Instruments	5,677,000	
Scaling factor	0.8	unitless
Power Block	941,000	2012$/1 MW
Molten Salt	2.65	2021$/1 MJ
Operational Costs	1–5	% of Capex/year
Equity IRR	10	%
Debt/Equity ratio	80/20	%

reduce the flexibility of the Carnot Battery to match the physical constraints of operating large-scale thermal systems [13, 14, 18, 31–33].

With the dispatch modeled, there is a second level of optimizations carried out which determines the design variables without calculating all possible arrangements. This is a genetic algorithm with adaptive mutation. The algorithm tests for different Key Performance Indicators (KPIs) such as Internal Rate of Return (IRR), and Net Present

Value (NPV) and evaluates the trends by mimicking natural evolutionary phenomena. The model needs only to demonstrate that there are economically feasible constellations for a Carnot Battery. The goal ultimately is to make test an argument for Carnot Batteries. A specific design decision for the construction of Carnot batteries is beyond the scope of this paper.

The financial optimization is carried out with a genetic algorithm. In short, a genetic algorithm mimics features of the evolutionary process to optimize a parameter. It has two processes to create new design variables combinations to be tested: crossover and adaptive mutation. The genetic algorithm is a balance between creating new configurations to be tested and learning from the previous populations whose features lead to financially attractive battery configurations. After a set number of generations, the model is artificially determined to have reached saturation [34].

Table 2 shows the assumed pricing for the sizing analysis. With the exception of the power block, the molten salts, and the operational costs a scaling was applied which reduces the costs of larger systems to reflect the economy of scale{Citation}. The financing used was 80% debt and 20% equity with fixed equity IRR. The pricing of the components was taken from the literature [20, 35] and a Chemical Engineering Plant Cost Index conversion from the year of the publication to 2022 valutas. The direct electric heater and operational expenditures were estimated.

4 Results and Discussion

The results of the analysis point to a clear Pareto curve pattern for the economic results. Countries with more varied electricity prices are more hospitable to Carnot batteries as there are more opportunities to make use of price differences throughout the year.

As this analysis for Romania pictured in Fig. 3, the country with the highest variability in electricity prices, shows, there are feasible design variables that yield positive economic results even with stricter assumptions regarding the operational costs and what percentage of the power block can be re-utilized. Of the 685 configurations tested for Romania, 12 had an acceptable IRR ranging from 5.3 to 6.7%, a positive NPV ranging from 1 to 87 M€, and a high capital expenditure from 260 to 545 M€. Other electricity markets prove less hospitable. France has a few coal-fired power plants to be retired and a stable electricity price (not pictured). Germany has many unique sizes of retiring coal-fired power plants but a stable electricity market. Of the 3084 configurations tested for Germany, only 5 exceptionally large systems prove to be profitable. Even with non-conservative assumptions, at operational costs at 1% of capital expenditures and 25% of Power block costs, configurations above 2,500 M€ to achieve positive NPV and IRR, making such a project difficult to fund.

Two factors vary across various bidding zones. The first is the number and different unique sizes of retiring coal-fired power plants. Secondly, depending on the variability of the energy market, a Carnot Battery is better or worse able to make use of the low and high prices.

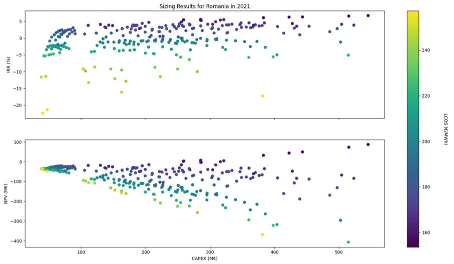

Fig. 3. IRR (top) and NPV (bottom) by Capital Expenditures Colored by LCOS. Results of the optimization for the Romanian electricity market.

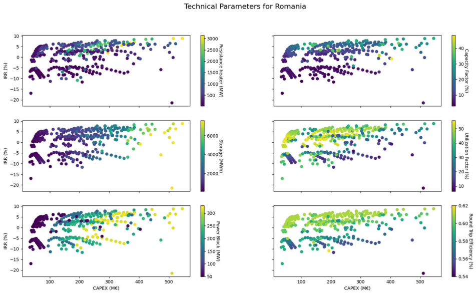

Fig. 4. Results of the optimization colored by design and technical parameters. From top to bottom design variables, electric heater, storage capacity, and power block on the left. The right side technical indicators are capacity factor, utilization factor, and round-trip efficiency.

Figure 4 shows trends in the results from which useful design insights can be drawn. The technical parameters show specific trends. A high Utilization Factor or Capacity Factor is not a predictor of the point being in the economic Pareto front. There is a trade-off between technical and economic factors. The efficiency of the overall system on the other hand was consistently at the peak value along the Pareto front. It is therefore an economically relevant technical factor.

Furthermore, in combination with the hourly carbon dioxide emissions of the grid, it is possible to map out the impact of the different configurations as seen in Fig. 5. Although the price and the emissions of a given hour are not directly correlated the battery does, in this marginal analysis, reduce the emissions even though there is no signal given to target lowering emissions. Note how more economically successful, larger systems have better carbon impact.

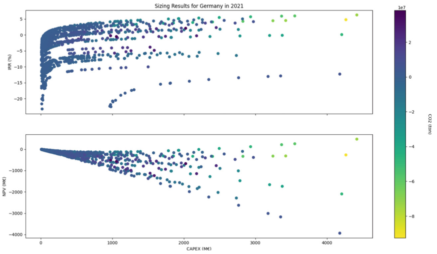

Fig. 5. IRR (top) and NPV (bottom) by CAPEX Results of configurations and their impact on Global Warming Potential per year for Germany with non-conservative assumptions for power block and operational costs.

5 Conclusion

Based on the methods and results outlined here, insights are summarized, and further studies are to be considered.

- There are techno-economically feasible arrangements for repurposing coal-fired power plants in the European electricity market.
- Carnot batteries should be considered as an option when determining the fate of closing coal-fired power plants, especially in volatile electricity markets or if markets become more volatile.
- Efficiency determines the feasibility of the battery.
- Carnot batteries can have a negative carbon impact in their usage, even when only guided by price signals.

There are several venues for future studies. There is a social aspect to the discussion of retiring and repurposing coal-fired power plants which are not addressed but is worth noting. By avoiding stranded assets, local economic areas based around the retiring coal-fired power plants can thrive. The human capital which has an in-depth knowledge of the power plants in question can be maintained. However, the importance of keeping operational expenditures down can run counter to this idea. It is worth exploring what is the social costs and benefits.

The study could also be built upon. Since the thermal power is well studied a more detailed thermodynamic analysis of the substitution can be modeled. Another aspect worth mentioning is the effect of the coal-fired power plant's closure and its substitution by storage both on the local grid and the national level. The results shown here are marginal. In an additional analysis, prices are hypothesized to become more stable.

The results here can be seen as an exploratory study into a subject that is often alluded to but has not been directly addressed in the scientific literature. It can be expanded upon. One advantage of using thermal batteries not explored here is the ease at which they can provide (at higher efficiencies) thermal energy as well as power. Integrating heating needs into the existing base code makes it possible to compare it to running the battery purely as electricity and the costs of providing the heating through other means. Several industries require heat, and they can benefit from a more stable energy pricing schema.

In either of these analyses, a more fine-grained case study perspective can give further insight into repurposing coal-fired power plants.

This is an argument for further exploration of the Carnot Batteries. Bidding zones with more variable markets are better suited for the implementation of Carnot batteries as alternatives to repurposing coal-fired power plants. Finally, the model is open source so it can be transparently criticized or improved [36].

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