Storing Electricity with Industrial Heat Pumps: Carnot Batteries for Grid-Level Energy Storage

Hannah Romberg, Sebastian Ostlender, Christian Vering, Dirk Müller, Germany

To mitigate environmental impacts, there is an urgent need to reduce CO_2 emissions in all sectors. In particular, electrification of energy-intensive processes is the key to avoiding CO_2 emissions aiming at the full provision of electricity from renewable energy sources [1]. However, electricity generation from renewable energy sources depends highly on time-variant boundary conditions, e.g. sun or wind, and is hence not permanently available. To overcome the availability gap, efficient electricity storage systems are essential as they shift energy from low-demand periods to high-demand periods [2]. Today, Pumped Hydro Energy Storage (PHES) is the predominant grid-scale electricity storage technology proven to be technically and economically viable, making up 95 % of the overall global storage capacity [3]. However, for most electrified systems, the easily-exploitable potential is almost exhausted [4]. Alternative electricity storage solutions must therefore be investigated and brought to market.

Electricity storage solutions are typically characterized by their power-to-capacity ratio, charge and discharge time, energy density, and specific costs. Hence, matching each technology to a specific application case is essential to exploit the entire electrification potential at all scales. Especially at grid-scale, systems are designed to operate for more than four hours. They require high storage capacities of typically more than 100 MWh and low discharge times, resulting in power-to-capacity ratios of about 1/4 h^1. Furthermore, the urgent need for market deployment calls for unit costs to be as cheap as possible, ruling out concepts based on lithium-ion batteries [5].

Avoiding material bottlenecks when only focusing on one technology, these requirements shift the focus of discussion toward alternative storage concepts. Although efficiencies of alternative concepts in most cases cannot compete with lithium-ion batteries, there are many studies investigating [6]. One option is called Carnot Batteries (CB). CB combine heat engines with thermal energy storage systems: electricity is stored as thermal exergy and recovered during discharge [7]. The charging process can be performed with a large-scale heat pump or any other technology using electricity to elevate thermal energy from a low to a higher temperature level. When using a heat pump, the discharge process is performed with an Organic-Rankine-Cycle (ORC) heat engine. This article aims to give a comprehensive introduction to Carnot Batteries for grid-scale electricity storage and motivates an integrated design approach for large-scale heat pumps as a key component.

Carnot Batteries: definition and characteristic

The term Carnot Battery refers to a set of technologies based on a concept originally proposed in 1922 by Marguerre [8]. Dumont et al. [7] provide a definition according to which a CB is primarily used to store electricity. An electric input is used to create a temperature difference between a high and a low-temperature reservoir. When discharging, the heat flows with the thermal gradient from the high to the low-temperature reservoir, powering a heat engine whereby a fraction of the electrical input is recovered. The definition is illustrated in Figure 1. Following the definition, the storage concept of pumped thermal energy storage (PTES) belongs to CB as well as other concepts such as liquid air storage or Lamm-Honigmann storage.

CBs comprise a low technology readiness level [7]. To push CBs to the market, it is promising to focus on commercially available equipment. A promising concept is based on the Rankine cycle [7]. The charging process is thereby realized with a vapor compression heat pump and the discharging process with a steam or an organic Rankine cycle (ORC), depending on the temperature level. A charging process with an electric heater is also possible [9]; however, since renewably generated electricity is highly limited in the next years, optimal use of electricity from renewable energy sources should be provided with a heat pump, even if it still leads to higher investments than electric heaters.

The overall efficiency of CBs depends on the coefficient of performance (COP) of the heat pump COP_{LSHP} and the efficiencies of the storage system η_{TES} and the ORC η_{ORC}. It is calculated according to Equation (1).

Equation (1).

$$\eta_{CB} = COP_{LSHP} \cdot \eta_{TES} \cdot \eta_{ORC}$$

The thermodynamic limit of such a system can be evaluated by considering two reversible Carnot cycles and an ideal storage system ($\eta_{TES}=1$) [10]. In this case, the overall efficiency does only depend on the temperatures of the high T_H (storage temperature) and of the low-temperature reservoir T_L (ambient temperature) and reaches 100 %, as shown in Equation (2).

Equation (2).

$$\eta_{CB,ideal} = COP_{Carnot,LSHP} \cdot \eta_{Carnot,ORC} = \frac{T_H}{T_H - T_L} \cdot \left(1 - \frac{T_L}{T_H}\right) = 1$$

Losses in the energy conversion processes impair the potential of CBs resulting in lower efficiencies. The overall efficiency depends highly on the temperature levels of both reservoirs. An apparent solution is using the ambient air as the low-temperature reservoir and, thus, as the heat source for the heat pump. For the ORC to work properly, the high-temperature reservoir should lay above 100 °C [11]. However, the temperature gradient yields to poor heat pump efficiencies. An alternative is using additional heat sources, for example, waste heat [7]. Integrating additional heat sources allows to reduce of the temperature gradient and hence improves the heat pump efficiency. The implied sector-coupling potential is hence worth investigating, subject to the availability of suitable heat sources [12].

Large-Scale Heat Pump

Following equation (1), the thermodynamic estimation shows that the COP of the large-scale heat pump (LSHP) has a huge impact on the overall efficiency. The COP of a heat pump itself is influenced by many factors. On one hand, the thermodynamic potential is limited by the temperature-dependent COP_(Carnot, LSHP). On the other hand, the operating point dependents energy conversion losses.

When designing a heat pump, one must consider the choice of refrigerant, the flow rate and the sizing of the components (e.g. compressor, heat exchanger, expansion valve) [13]. The choice of refrigerant is directly related to the required temperature levels due to its thermodynamic properties. At the same time, the choice of refrigerant influences the energy conversion efficiency. Among others, the isentropic efficiency of the compressor is influenced by the choice of refrigerant [14]. Furthermore, the refrigerant changes the requirements on the heat exchangers, for example, if refrigerant mixtures with temperature glide are used. In addition to the sizing, the operational strategy, including the controller design, takes on a decisive role in an efficiently performing machine. The part load behaviour, the compressor's operational envelope, superheating, and subcooling are major aspects that influence efficiency.

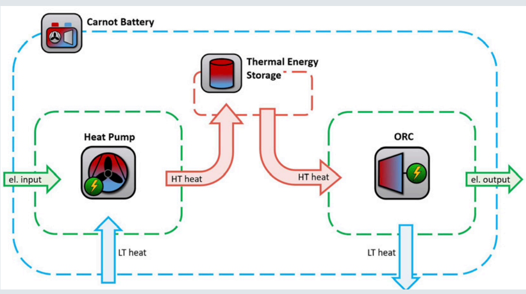

Figure 1: Graphical definition of a CB with its components (heat pump, thermal energy storage, ORC) and energy flows (electrical (el) energy, high temperature (HT) heat, low temperature (LT) heat).

Due to the underlying complexity, studies have investigated the possibilities of integrated system design methods for heat pumps in the building sector with outputs of up to 20 kW [13]. These design methods include all the mentioned aspects in the design process and result in a more efficient heat pump for a specific use case.

CBs call for large-scale heat pumps with power outputs higher than 10 MW and temperature levels reaching 80 °C in comparison to heat pumps for buildings. These different requirements lead to new degrees of freedom in the design decision process, increasing the overall solution space and making it an even more complex task. The development of heat sources that may not be feasible due to its economics for small systems may become attractive for large-scale systems. Possible scenarios include the use of residual heat in wastewater from the sewer system, river water as a heat source, or waste heat from industrial processes or data centers. Furthermore, the options for designing heat pumps are expanding. The use of alternative refrigerants, such as ammonia subject to special safety regulations and flow sheets, becomes attractive to maximize the energy conversion efficiency. Moreover, the use of compressor technologies such as flow compressors becomes possible.

When widening the scope to the whole CB, the design task becomes even more complex. Next to the individual component design of storage and ORC, the interaction between components becomes crucial. In particular, the use of a large-scale heat pump with a storage system represents a challenging operational scenario due to a highly transient operating behavior. To meet these challenges, future work should develop an integrated design method for CBs considering the design and operation of all components and maximizing the efficiency of the system.

Conclusion

When widening the scope to the whole CB, the design task becomes even more complex. Next to the individual component design of storage and ORC, the interaction between components becomes crucial. In particular, the use of a large-scale heat pump with a storage system represents a challenging operational scenario due to a highly transient operating behavior. To meet these challenges, future work should develop an integrated design method for CBs considering the design and operation of all components and maximizing the efficiency of the system.

HANNAH ROMBERG,
RWTH AACHEN UNIVERSITY
Germany
hannah.romberg@eonerc.rwth-aachen.de
https://doi.org/10.23697/cbr3-z037