

ON THE INHERENT IMBALANCE OF HEAT PUMP BASED CARNOT BATTERIES

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Content

Achieving climate neutrality requires a fundamental transformation of the energy sector, with a significant expansion of renewable but fluctuating electricity generation. To ensure supply security, these intermittent sources must be complemented by large-scale energy storage systems. The Carnot Battery (CB) is a promising and scalable concept which converts electricity into thermal energy and back, while also enabling direct heat and cold exports.

The charging phase deploys electrical heaters or heat pumps. The discharging phase can deploy a range of heat engine technologies, typically Rankine- or Brayton-cycle based [1]. CBs are proposed as an alternative to large-scale electrical energy storage system such as pumped hydro energy storage or compressed air energy storage, as the components used are well scalable, both in terms of size and cost and do not have any specific geographical requirements [2].

If the charging cycle of the CB uses a heat pump process, typically thermal energy storage is considered at the hot and cold end of the process. A key challenge during operation of these systems is the *imbalance* — a thermal asymmetry between the hot and cold storage units resulting from different component efficiencies and thermal exports (if present). A schematic representation of the two types of imbalances (indicated with subscript “imb”) is displayed in Figure 1.

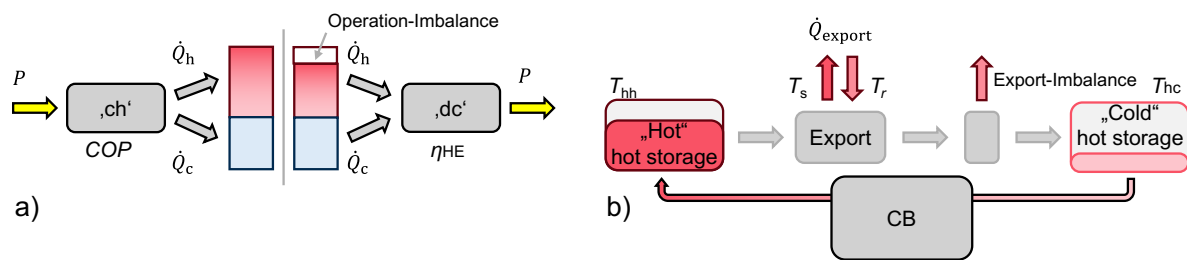


Figure 1 Schematic representation of a) operation imbalance, b) export imbalance

The imbalance reduces the effective coefficient of performance (*COP*), the overall round-trip efficiency (*RTE*) and economic performance of the system, yet its influence has not been systematically analyzed in previous research. Thus, the present study will fill this gap by analysis the operation imbalance of three representative configurations: transcritical CO₂, Air-Brayton and Water-Rankine.

Methods

The objective of this work is to perform a theoretical assessment of imbalance effects in heat pump-based CBs. As all three investigated systems exhibit sensible heat transfer, the Lorentz formula is employed and evaluated for different quality factors (ϑ) and storage temperatures (T_h and T_c) to evaluate *RTE* of the systems. The Lorentz formular for the charging and discharging process follows:

$$COP = \eta_{L,ch} \cdot \vartheta = \frac{T_{m,h}}{T_{m,h} - T_{m,c}} \cdot \vartheta \quad (1)$$

$$\eta_{HE} = \eta_{L,dc} \cdot \vartheta = \frac{T_{m,h} - T_{m,c}}{T_{m,h}} \cdot \vartheta \quad (2)$$

$$T_{m,h} = \frac{T_{hh} - T_{hc}}{\ln(T_{hh}) - \ln(T_{hc})} \quad (1)$$

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$$T_{m,c} = \frac{T_{ch} - T_{cc}}{\ln(T_{ch}) - \ln(T_{cc})} \quad (2)$$

The product of Eq. (1) and Eq. (2) equals RTE .

A formular for operation imbalance is derived by comparing the heat-to-cold-ratios of the charging and the discharging process:

$$\dot{Q}_{imb,operation} = \dot{Q}_{c|ch} \cdot \left(\frac{\dot{Q}_h}{\dot{Q}_c} \Big|_{ch} - \frac{\dot{Q}_h}{\dot{Q}_c} \Big|_{dc} \right) = P_{ch} \cdot (COP - 1) \cdot \left(\frac{COP}{COP - 1} - \frac{1}{1 - \eta_{HE}} \right) = P_{ch} \cdot \frac{1 - RTE}{COP - RTE} \quad (5)$$

Assuming that the same cold power shall be produced/used in the charging/discharging cycle, the waste heat ($\dot{Q}_{imb,operation}$), which needs to be discharged, can be calculated. For better reference, three systems will be exemplary compared based on commercial architectures: a transcritical CO₂-based system (tCO₂, ETES design of Everllence [3]), a water-steam-based system (Water-Rankine, SEMS design of Malta [4]) and an air-based Brayton system (Air-Brayton, OPTES design of Storasol [5]).

Export imbalance is assessed by comparing the return temperature (T_r) of the export process with the "cold" storage temperature (T_{hc}) (in Figure 1 illustrated for a thermal export from the hot storage):

$$\dot{Q}_{imb,export} = \dot{Q}_{h,ch} \cdot \frac{\dot{Q}_{export}}{\dot{Q}_{storage}} = \dot{Q}_{h,ch} \cdot \frac{\int_{T_{hc}}^{T_r} c_p(T) dT}{\int_{T_{hc}}^{T_{hh}} c_p(T) dT} \quad (6)$$

However, this analysis is highly system dependent. As a result, the analysis of the thermal export imbalance will be demonstrated on a specific system layout taken from literature, namely the transcritical CO₂-based Carnot battery system, which is envisioned as a trigeneration system [1][2].

Results

Generally, operation imbalance increases for low COP and for low RTE . The impact of COP is more pronounced compared to RTE . The relative impact of COP increases the higher RTE . For a pure electricity storage system, the *operation imbalance* should be minimized to maximize the utilization of the heat produced. To achieve this, two options exist: first, the system's COP should be maximized, which leads to a low temperature system such as the tCO₂ system. The second option suggests RTE maximization through more efficient subsystems, which leads to the Water-Rankine system and generally to more complex systems, thus higher equipment cost. If connected to a heat consumer, a significant fraction of *operation imbalance* can be exported as useful heat. In low-temperature systems, *export imbalance* can reduce the usable share of *operation imbalance* as well as heat export, whereas high-temperature systems benefit from broader compatibility with the required temperature of industrial heat demands. Even under favorable conditions, perfect balance remains unlikely, as *operation imbalance* follows electricity market-driven charging patterns rather than heat demand. Providing an environmental heat rejection path increases operational flexibility but reduces effective RTE .

For *export imbalance*, the system under investigation is a tCO₂ CB. The hot storage medium is (pressurized) hot water operated between 15-150 °C. The *export imbalance* is investigated for two return temperatures: 45 and 65 °C, which correspond to comparatively new and old district heating networks, respectively. The *export imbalance* can then be applied to the COP of the system to evaluate the effective performance of the thermal export (COP_{eff}). As expected, the COP_{eff} suffers the higher the return temperatures as more heat needs to be discharged. While the *export imbalance* is around 22 % for a return temperature of 45 °C, it increases to around 37 % for a return temperature of 65 °C.

The results suggest that neither low- and high-temperature systems should be operated solely as electricity storage but integrate heat export considerations from the outset to maximize the utilization of the charged energy. "Commercial" systems follow this approach **Fehler! Verweisquelle konnte nicht gefunden werden.**[4].

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