ON THE INHERENT IMBALANCE OF HEAT PUMP BASED CARNOT BATTERIES

Nils Hendrik PETERSEN[1], Robert SAGER[1], Manfred Wirsum[1]

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.

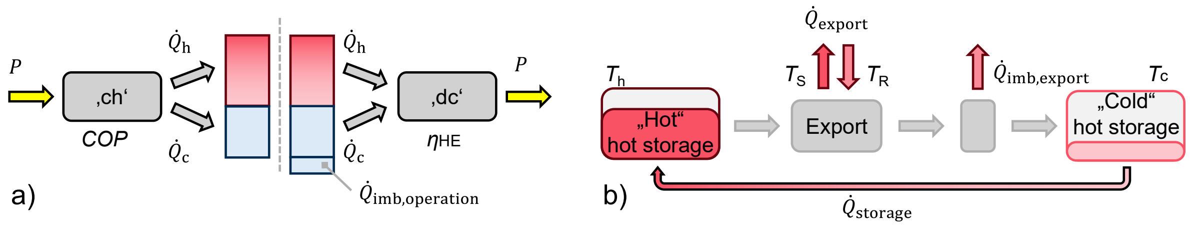

Figure 1 Schematic representation of a) operation imbalance, b) export imbalance

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.

Methods

The objective of this work is to perform a theoretical assessment of imbalance effects in heat pump-based CBs. For this purpose, the Carnot formular is employed and evaluated for different Carnot efficiencies (ϑ), storage temperatures (T_h and T_c) and pinch point temperature differences (ΔT_{PP}) to evaluate *RTE* of the systems. The Carnot formular for the charging and discharging process follows:

$$COP = \eta_{C,ch} \cdot \vartheta = \frac{T_h + \Delta T}{(T_h + \Delta T) - (T_c - \Delta T)} \cdot \vartheta = \frac{T_{hh,PP,adj}}{\Delta T_{PP,adj}} \cdot \vartheta \quad (1)$$

$$\eta_{HE} = \eta_{C,dc} \cdot \vartheta = \frac{(T_h - \Delta T) - (T_c + \Delta T)}{T_h - \Delta T} \cdot \vartheta = \frac{\Delta T_{PP,adj}}{T_{hh,PP,adj}} \cdot \vartheta \quad (2)$$

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:

[1] Institut für Kraftwerkstechnik, Dampf- und Gasturbinen, RWTH Aachen University, Mathieustraße 9, 52074 Aachen, +4924126725., petersen@ikdg.rwth-aachen.de, ikdg.rwth-aachen.de

$$\dot{Q}_{\text{imb,operation}} = \dot{Q}_{\text{c|ch}} \cdot \left(\frac{\dot{Q}_{\text{h}}}{\dot{Q}_{\text{c}}}\bigg|_{\text{ch}} - \frac{\dot{Q}_{\text{h}}}{\dot{Q}_{\text{c}}}\bigg|_{\text{dc}} \right) = P_{\text{ch}} \cdot (COP - 1) \cdot \left(\frac{COP}{COP - 1} - \frac{1}{1 - \eta_{\text{HE}}} \right) = P_{\text{ch}} \cdot \frac{1 - RTE}{COP - RTE} \quad (3)$$

Assuming that the same cold power shall be produced/used in the charging/discharging cycle, the waste heat ($\dot{Q}_{\text{imb,operation}}$), which needs to be discharged, can be calculated. For better reference, three relevant systems will be exemplary compared: a transcritical CO2-based system (tCO2), a water-steam-based system (CHEST) and an air-based Brayton system (Brayton).

Export imbalance is assessed by comparing the return temperature (T_R) of the export process with the “cold” storage temperature (T_C) (in Figure 1 illustrated for a thermal export from the hot storage):

$$\dot{Q}_{\text{imb,export}} = \dot{Q}_{\text{hot,ch}} \cdot \frac{\dot{Q}_{\text{export}}}{\dot{Q}_{\text{storage}}} = \dot{Q}_{\text{hot,ch}} \cdot \frac{\int_{T_{\text{ch}}}^{T_{\text{return}}} c_{\text{p}}(T)dT}{\int_{T_{\text{ch}}}^{T_{\text{hh}}} c_{\text{p}}(T)dT} \quad (4)$$

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

The results show that ΔT_{PP} reduces RTE more distinct in case of low temperature CB systems, such as the tCO2 process. This was expected as the relative impact of ΔT_{PP} on the Carnot formulars is more pronounced for low temperature systems. This relative trend is in line with the findings of [1]. Although it must be mentioned that for lower Carnot quality, the *RTE* of the three systems converge, highlighting the relatively higher impact of turbomachinery efficiency on the CHEST and Brayton process, which is in line with the relative findings of [1], too.

The imbalance is a function of *COP* and *RTE* (compare Eq. 3): if either value decreases, the imbalance increases. However, a decrease in *COP* does not necessarily yield a decrease in *RTE*: Looking at high temperature systems, the *COP* is inherently lower compared to low temperature systems due to the higher temperature lift to be provided. However, *RTE* can be constant as η_{HE} increases according to the Carnot formular. As a result, the imbalance increases for high temperature systems at the same *RTE*.

The export imbalance analysis shows that the system design must match the anticipated heat consumer temperature profile, i.e., supply temperature (T_S) and T_R, to effectively reduce export imbalance. To meet T_S of the heat consumer, a sufficiently high storage temperature must be realized. For T_R of the heat consumer, either a residual temperature discharge must be realized to keep T_C or higher T_C must be accepted. While the former must be accounted for as an additional loss, the latter leads to lower *RTE* as the exergetic loss through heat transfer is increased for the discharging process. The analysis highlights that the CB storages design must consider the associated thermal export system from the design phase on, further limiting the design space of CBs, which are operated as a trigeneration system.

References

[1] Steinmann, W., Jockenhöfer, H. and Bauer, D. (2020), Thermodynamic Analysis of High-Temperature Carnot Battery Concepts. Energy Technol., 8: 1900895. https://doi.org/10.1002/ente.201900895

[2] Frate, Guido Francesco & Antonelli, Marco & Desideri, Umberto. (2017). A novel Pumped Thermal Electricity Storage (PTES) system with thermal integration. Applied Thermal Engineering. 121. 10.1016/j.applthermaleng.2017.04.127.

[3] Sanz Garcia, Luis & Jacquemoud, Emmanuel & Jenny, Philipp. (2022). Large Scale Tri-Generation Energy Storage System for Heat, Cold and Electricity based on Transcritical CO2 Cycles.