

ON THE INHERENT IMBALANCE OF HEAT PUMP BASED CARNOT BATTERIES

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Kurzfassung: Carnot batteries (CB) are discussed as large-scale electricity storage systems that can simultaneously provide heat and cold. However, their performance is constrained by *operation imbalance* and *export imbalance*, which arise from the mismatch between charging and discharging efficiencies and from temperature mismatches between storage and thermal consumers. This work presents a systematic analysis of these imbalance mechanisms and evaluates their impact on three CB concepts.

Based on the Lorentz equation and the given storage temperatures of the three CB, the individual subsystem's performances are derived. From the given roundtrip efficiencies (*RTE*) quality factors are derived. The *operation imbalance* is considered as surplus heat, quantified analytically as a function of coefficient of performance (*COP*) and *RTE*. *Export imbalance* is assessed by comparing storage temperature profiles with representative heat consumer temperature profiles. The analysis covers low-temperature transcritical CO₂ systems as well as high-temperature molten-salt-based concepts such as Water-Rankine and Air-Brayton.

The results show that low-temperature systems achieve high *COP* and thus comparatively low *operation imbalance*. High-temperature systems exhibit pronounced *operation imbalance*, which must be managed through heat export or dissipation. While the former increases overall energy utilization, *export imbalance* limits the usable fraction, particularly for low-temperature systems. Perfect balance requires an exact match between storage and consumer temperature profiles; a condition rarely met in practice.

The findings highlight that imbalance is a central design constraint for CB. Meaningful assessment of CB performance therefore requires joint consideration of operational strategy, temperature level, and heat integration from the earliest design stages.

Keywords: Thermal Export, Electricity Storage, Trigenation, Mixed-Integer Linear Programming

1 Introduction

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 [1]. 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. CBs are proposed as an alternative to large-scale electrical energy storage systems 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].

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 [3]. A good overview of CB is given in [4].

A schematic graphical representation of a CB is displayed in Figure 1.

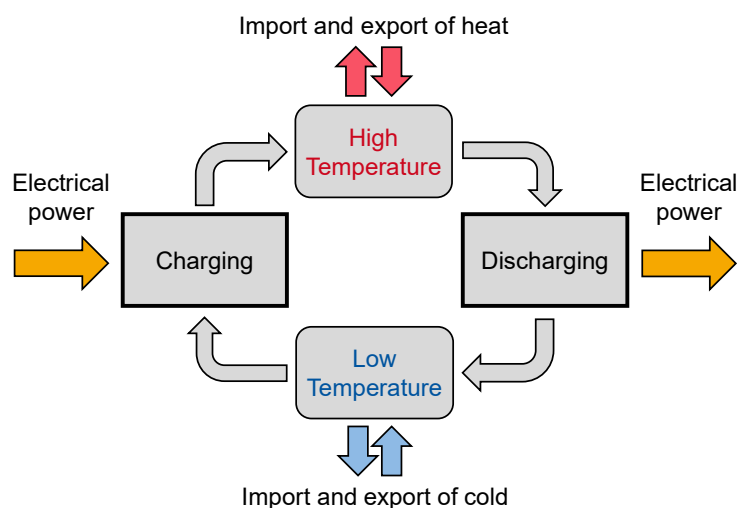


Figure 1 Schematic representation of CB

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 capacity resulting from different cycles for the charging and the discharging process, machine inefficiencies and pinch point temperature differences within the heat exchangers (among others) as well as unmatched thermal profiles during thermal exports (if present). These origins of imbalance can be classified in two categories: *operation imbalance* and *export imbalance*. A schematic representation of both types of imbalances is displayed in Figure 2.

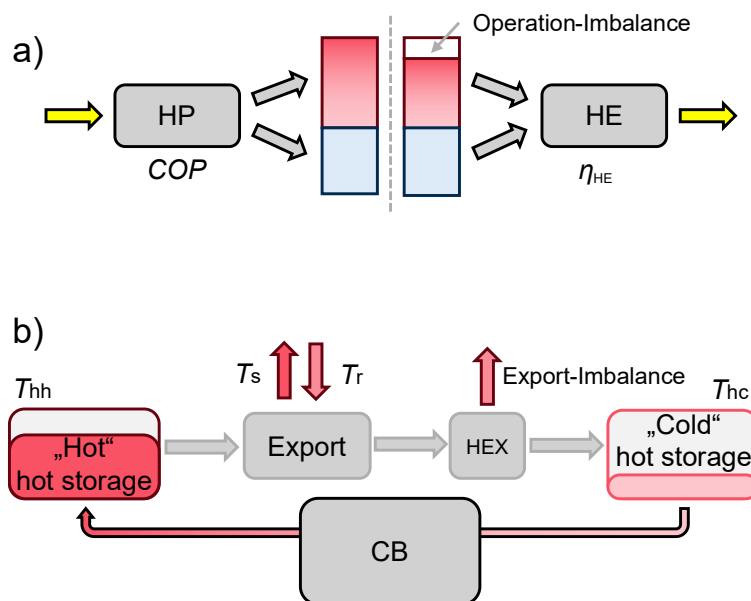


Figure 2 Schematic representation of a) operation imbalance, b)

For the *operation imbalance*, the unmatched heat-to-cold ratios of the charging and discharging process leads to an inherent surplus of heat. As a result, two different effects can be observed: first, if the hot storage is undersized or equally sized compared to the cold storage, the hot storage would run full; second, for an oversized hot storage compared to the cold storage, the cold storage would run full. An equally sized storage system here refers to a capacity ratio between hot and cold storage equal to the coefficient of performance (*COP*) of the heat pump process. To move the system back into equilibrium, there are three options:

- 1) discharge to the environment,
- 2) export to a heat consumer,
- 3) compensation by an additional refrigeration system.

However, as the latter adds more complexity to an already complex system, it is not further evaluated at this stage. If a heat pump-based CB system is connected to a heat consumer, the inherent *operation imbalance* can be leveraged for further earnings for the system operator. If considered as a pure electricity storage system, however, this surplus heat must be considered as an additional loss, which reduces the effective *COP*, the overall round-trip efficiency (*RTE*) and economic performance of the system. Although *operation imbalance* is widely known and accounted for in literature, a systematic assessment across CB concepts is still missing. Thus, the present study will fill this gap by analysis the operation imbalance of three representative configurations: transcritical CO₂, Air-Brayton and Water-Rankine.

In case of a thermal export, an additional source of imbalance might occur: the *export imbalance*. Principally, thermal export imbalance can occur only on the hot side. In case of hot thermal export, if the hot storage temperature profile does not match the temperature profile of the heat consumer, namely if the return temperature of the heat consumer is higher than the "cold" hot storage temperature, additional heat must be discharged. If the export imbalance is not discharged, the "cold" hot storage temperature would increase in temperature, which reduces the effective storage capacity and negatively affects the charging and the discharging process performance of the CB. In case of present temperature glides on the hot end of the

CB process (for example for transcritical CO₂ or Brayton-based processes), this would lead to exergy destruction as the thermal profiles would further diverge.

Export imbalance is conceptually introduced by Sanz Garcia et al. [5]. They investigated the impact of *export imbalance* on the effective *COP* of the thermal export as a function of supply and return temperature of the heat consumer. They found that *export imbalance* increases with both return and supply temperature. However, if the system design is fixed and the hot storage temperature is sufficiently high, the *export imbalance* should be independent¹ of the supply temperature. The authors claim that the supply temperature has an impact on the required pressure ratio of the charging cycle. While this is correct, it indicates that the authors optimized each cycle to the respective heat consumer temperature profile. The associated *RTE* of these cycles is missing. Thus, no general conclusion for a bi-generation system can be drawn. This work aims to close that gap.

2 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 equation is employed and evaluated for different quality factors (ϑ), storage temperatures (T_h and T_c) to evaluate *RTE* of the systems.

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

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

$$T_{m,h} = \frac{T_{hh} - T_{hc}}{\ln(T_{hh}) - \ln(T_{hc})} \quad (3)$$

$$T_{m,c} = \frac{T_{ch} - T_{cc}}{\ln(T_{ch}) - \ln(T_{cc})} \quad (4)$$

The Lorentz equation can be multiplied with the quality factor ϑ , leading to the efficiencies of the charging and the discharging process:

$$COP = \eta_{L,ch} \cdot \vartheta \quad (5)$$

$$\eta_{HE} = \eta_{L,dc} \cdot \vartheta \quad (6)$$

ϑ is representing all losses such as finite temperature difference within the heat exchangers, machine efficiencies, etc.

The theoretical *RTE* of the system can be assessed by the following formula:

$$RTE_{theo} = COP \cdot \eta_{HE} \quad (7)$$

¹ In case of sensible heat transfer and non-constant fluid properties, the supply temperature might have an impact when finite temperature differences are considered within the heat exchangers.

A formula for *operation imbalance*, $\dot{Q}_{\text{imb,operation}}$, is derived by comparing the heat-to-cold-ratios of the charging and the discharging process:

$$\begin{aligned}\dot{Q}_{\text{imb,operation}} &= \dot{Q}_{\text{c|ch}} \cdot \left(\frac{\dot{Q}_{\text{h}}}{\dot{Q}_{\text{c}}}\Big|_{\text{ch}} - \frac{\dot{Q}_{\text{h}}}{\dot{Q}_{\text{c}}}\Big|_{\text{dc}} \right) = P_{\text{ch}} \cdot (\text{COP} - 1) \cdot \left(\frac{\text{COP}}{\text{COP} - 1} - \frac{1}{1 - \eta_{\text{HE}}} \right) \\ &= P_{\text{ch}} \cdot \frac{1 - \text{RTE}}{\text{COP} - \text{RTE}}\end{aligned}\quad (8)$$

Assuming that the same cold power shall be produced/used in the charging/discharging cycle, the surplus heat ($\dot{Q}_{\text{imb,operation}}$) can be calculated. In the representation of Equation (8), $\dot{Q}_{\text{imb,operation}}$ accounts for surplus heat, which needs to be discharged to the environment within the charging process. The position of surplus heat discharge can be different, for example in the discharge cycle. However, the impact on cycle performance is minor [6].

The *operation imbalance-adjusted RTE* (oi-adj) of a system can be assessed by the following formula:

$$\text{RTE}_{\text{oi-adj}} = \left(\text{COP} - \frac{1 - \text{RTE}}{\text{COP} - \text{RTE}} \right) \cdot \eta_{\text{HE}} \quad (9)$$

For better reference, three systems will be exemplary compared based on commercial architectures: a transcritical CO₂-based system (tCO₂, ETES design of Everllence [5]), a water-steam-based system (Water-Rankine, SEMS design of Malta [7]) and an air-based Brayton system (Air-Brayton, OPTES design of Storasol [8]). The associated information is displayed in Table 1.

Table 1 KPI of investigated storage systems

System	Hot medium	T_{hh} [K]	T_{hc} [K]	Cold medium	T_{ch} [K]	T_{cc} [K]	RTE [%]	Ref.
tCO ₂	Press. water	423	288	Ice / Glycol	270	266	40-60	[5]
Rankine	Molten salt	838	553	Press. water	363	393	>55	[7]
Brayton	Molten salt	823	495	n/a	300	180	66	[8]

Export imbalance is assessed by comparing the return temperature (T_r) of the export process with the “cold” (T_{hc}) and “hot” (T_{hh}) hot storage temperature (in Figure 1 illustrated for a thermal export from the hot storage) according to the following equation:

$$\dot{Q}_{\text{imb,export}} = \dot{Q}_{\text{h,ch}} \cdot \frac{\dot{Q}_{\text{export}}}{\dot{Q}_{\text{storage}}} = \dot{Q}_{\text{h,ch}} \cdot \frac{\int_{T_{\text{hc}}}^{T_r} c_p(T) dT}{\int_{T_{\text{hc}}}^{T_{\text{hh}}} c_p(T) dT} \quad (10)$$

However, this analysis is highly system and heat consumer dependent. As a result, the analysis of the thermal export imbalance will be demonstrated on a specific system layout taken from literature, namely the tCO₂-based Carnot battery system, which is envisioned as a trigeneration system [2][3][5].

3 Results

This section comprises the individual results obtained from the analysis of *operation imbalance* and *export imbalance*.

3.1 Operation Imbalance

As indicated by Equation (8), an analysis of *operation imbalance* requires knowledge not only of the performance on system level but also on subsystem level. Evaluating the given temperatures of the hot and cold storage media (presented in Table 1), Equation (1) and Equation (2) can be used to identify the subsystem's ideal performance. The results are given in Table 2.

Table 2 Calculated subsystem performance

System	$\eta_{L,ch}$ [-]	$\eta_{L,dc}$ [-]
tCO ₂	4.22	0.24
Rankine	2.24	0.45
Brayton	1.57	0.64

Assuming an equal distribution of inefficiencies from the ideal system performance, the quality factor is equal to the square root of the given *RTE*. The results are presented in Table 3.

Table 3 Calculated quality factors

<i>RTE</i> [-]	0.4	0.5	0.6	0.7
ϑ [-]	0.63	0.71	0.77	0.84

The ideal system's performance can now be combined with different quality factors to obtain the real system's and subsystem's performance using Equation (5) and Equation (6).

In the next step, the *operation imbalance* can be calculated following Equation (8) and the RTE_{oi-adj} can be calculated following Equation (9). The results are displayed in Figure 3.

The x-axis shows the calculated *COP* of the three investigated systems, the y-axis shows *RTE* (both RTE_{theo} and RTE_{oi-adj}). The calculated imbalance is displayed by means of a heat map. Moreover, four dashed lines indicate the four RTE_{theor} investigated. The markers are associated with the lines in ascending order: the lowest marker connects with the lowest dashed line and the highest marker connects with the highest dashed line.

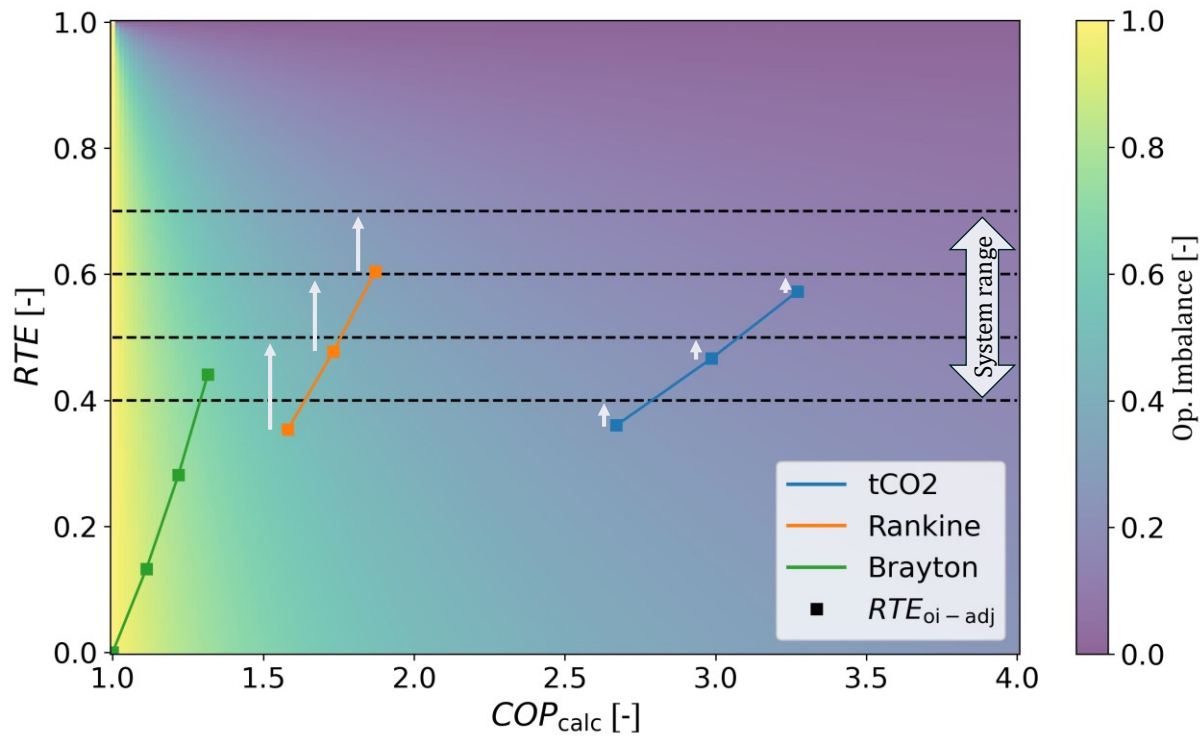


Figure 3 Calculated charging performance, operation imbalance and RTE_{oi-adj}

Figure 3 displays the general relationship between *operation imbalance*, *COP* and *RTE*: 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*. As a result, high temperature systems such as Brayton and Rankine suffer from high imbalance due to the comparatively low *COP*. This becomes exceptionally obvious for the Brayton system: the imbalance ranges between 49-100 %, resulting in a significant reduction of *RTE* up to a value of 0. This is trivial given the fact that principally no cold is produced if the *COP* approaches 1. This finding is less pronounced for the Rankine system as the *COP* is generally higher given the lower temperature lift (compare Table 1). For the Rankine system, imbalance ranges between 26-59 %, which reduces *RTE* down to 23-60 %. The lowest imbalance can be seen for the high *COP* system, namely the tCO₂ system. Imbalance ranges between 15-26 %, thus *RTE* reduces to 36-57 %.

An overview of the development of RTE_{theo} , RTE_{oi-adj} as well as the relative reduction is given in Table 4.

Table 4 Comparison of RTE_{theo} , RTE_{oi-adj} and relative reduction for the three investigated systems

System	RTE_{theo} [%]	RTE_{oi-adj} [%]	ΔRTE [%]
Brayton	40-70	0-48	37-100
Rankine	50-70	35-60	14-29
tCO ₂	40-60	0-44	5-10

3.2 Export Imbalance

As indicated by Equation (10), an analysis of the *export* imbalance requires substantial knowledge on the thermal export temperature profile as well as on the system temperatures, specifically the storage temperatures, potentially also the medium of the intermediate loop if the storage cannot be accessed directly by the heat consumer. As these variables are objective to optimization studies, this study can only serve as an indication of the impact of *export imbalance* on the system performance.

The system under investigation is a tCO₂ CB. As specified in Table 1, the hot storage medium is (pressurized) hot water operated between 15-150 °C. As an example, thermal export to a district heating network is investigated. This example seems plausible as the thermodynamic properties of CO₂ favor sensible heat transfer. Once the thermal storage temperatures are defined, the *export imbalance* depends only on the return temperature of the heat consumer.

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}). The results of this analysis are displayed in Figure 4.

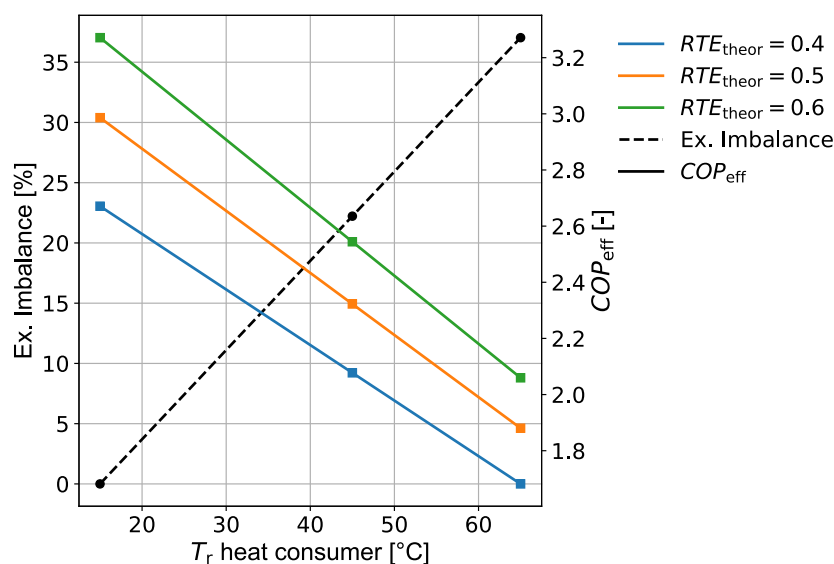


Figure 4 Export imbalance and effective thermal export COP as function of heat consumer's return temperature

The x-axis shows the return temperature of the heat consumer. The left y-axis shows the *export imbalance*, the right y-axis shows COP_{eff} . The three colored lines represent the *COP* associated with the three *RTE* investigated.

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. As a result, COP_{eff} decreases to around 1.7-2 from 2.7-3.3.

4 Discussion

In this section, the results presented in Chapter 3 shall be discussed.

4.1 Operation Imbalance

From the simple analysis presented in Chapter 3.1, it becomes clear that the choice of system and thus temperature has a significant impact on the *operation imbalance*, thus on the use case of the system. For a pure electricity storage system, the *operation imbalance* should be minimized to maximize the utilization of the heat produced, thus maximizing RTE_{oi-adj} . 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 Rankine system and generally to more complex systems, thus higher equipment cost.

Given the fact that typical high-temperature heat pumps can reach quality factors up to 70 % [9] and power generation technologies can reach quality factors up to 76 %², the high quality factor of 84 % seems ambitious.

For a bi-generation system, meaning electrical and thermal export, the *operation imbalance* can be provided to a heat consumer. However, several challenges remain: The temperature profile of the *operation imbalance* and the heat consumer must match for an efficient provision. In the first place, this considers that the supply temperature of the heat consumer is well below the hot storage temperature of the CB. In the second place, the penalty of *export imbalance* must be evaluated carefully. Another challenge is that the demand and supply of heat might diverge: The availability of surplus heat from the CB is coupled to its operational profile on the electricity side, particularly the charging process. Assuming that CB are considered as a (multi-) day storage system, charging might occur during times when there is vast renewable power generation within the electricity grid, for example during the day for PV. This gives a day-night schedule to the *operation imbalance* availability. Although the heat storage disconnects demand and supply, it must be considered that the surplus heat can also decrease the flexibility of the CB as it “occupies” usable capacity within the storages for re-electrification. As a result, it is suggested that the heat consumer should be sufficiently large and not rely solely on the CB *operation imbalance*. Consequently, the heat consumer must deploy additional heat generators to comply with security of supply requirements. However, it is questionable if such a heat consumer would pay this “unplanned” heat supply as it might disrupt its own heat generation schedule.

4.2 Export Imbalance

Thermal export imbalance strongly depends on the match between the hot storage temperature profile and the heat consumer's return temperature. For the high-temperature systems investigated, the hot storage medium is molten salt, thus the “cold” hot storage

² Evaluated based on Carnot equation, turbine inlet temperature of 1600 °C [10], ambient temperature of 15 °C and combined cycle efficiency of 64 % [11].

temperature is around 260 °C, which covers a wide range of industrial heat demands [9]. In such cases, thermal export imbalance is less critical, as the stored heat can be used directly.

For low-temperature systems such as tCO₂, the situation is fundamentally different as the “cold” hot storage temperature must be chosen as low as possible for *RTE* maximization [5]. This implies that the return temperature of a heat consumer will be likely between the “cold” and “hot” hot storage temperature. It follows that low-temperature Carnot batteries are particularly sensitive to the choice of heat consumers and their operating temperature levels. As a result, the export temperature profiles should be considered already during the design process, which leads to customized solutions with challenges for standardization and thus higher investment cost.

Operation imbalance generates surplus heat that can, in principle, be exported. However, this surplus is subject to *export imbalance* if the temperature profiles do not match. For example, for tCO₂, *operation imbalance* is between 15-26 %, which must be scaled with the *export imbalance* (22-37 %). As a result, the “real” imbalance loss is only around 3-10 %, while 12-16 % of *operation imbalance* can be exported to the consumer, effectively increasing the combined-heat-and-power efficiency. However, it follows that a perfect balance can only be achieved if the storage temperature profiles match the heat consumer’s temperature profile exactly. This condition is rarely met in practice, implying that a certain degree of imbalance is unavoidable in case of a bi-generation system.

True balance between hot and cold storage can only be achieved if both, heat and cold, are exported in a ratio that compensates *operation* and *export imbalance* simultaneously. In practice, this requires heat and cold consumers with sufficient capacity or flexibility in their demand profiles, e.g., by the introduction of storages. Such conditions are difficult to guarantee, as *operation imbalance* depends on the electricity market-driven operating profile of the CB rather than on heat consumer heat demand profile.

As a result, providing a controlled discharge path for surplus heat to the environment increases operational flexibility. It decouples electricity storage operation from heat demand profiles and allows the system to follow electricity price signals more closely. However, this flexibility comes at the cost of additional losses, which directly reduces the effective *RTE*.

5 Conclusion

This work analyzes *operation* and *export imbalance* in Carnot battery (CB) systems, which use heat pumps for charging, and shows that imbalance is not a secondary effect but a defining characteristic that strongly shapes feasible use cases. The results demonstrate that system temperature level, subsystem performance, and the intended mode of operation, pure electricity storage versus combined electricity and heat export, jointly determine achievable roundtrip efficiency (*RTE*).

The analysis is based on a unified, thermodynamically consistent framework using the Lorentz equation combined with realistic quality factors for the performance of the charging and discharging process. This approach enables a transparent comparison across system concepts while maintaining a clear link between idealized limits and practical performance. *Operation imbalance* is quantified analytically from *RTE* and *COP*, while *export imbalance* is evaluated by comparing storage temperature profiles with heat consumer return temperatures.

This separation allows the combined impact of both imbalance mechanisms to be assessed without relying on detailed component-level models.

The results show that minimizing *operation imbalance* is essential for pure electricity storage applications, favoring low-temperature systems with high *COP*. However, low-temperature systems generally exhibit lower *RTE* given the low share of exergy stored [3]. High-temperature systems, however, exhibit higher *RTE* but suffer from higher *operation imbalance*. 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*.

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 [5][7].

Future work should extend the methodology beyond the Lorentz-based approximation to cycle-specific models that better capture real operating characteristics. In addition, flexible operation under realistic dispatch, including start-up, shut-down, and dynamic load changes, must be analyzed to quantify imbalance and loss mechanisms under non-steady conditions.

6 Nomenclature

Abbreviations		
Symbol		Name
Brayton		Brayton-based Carnot battery
CB		Carnot battery
Rankine		Rankine-based Carnot battery
tCO ₂		Transcritical CO ₂

Greek Symbols		
Symbol	Unit	Name
η	-	Efficiency
ϑ	-	Quality factor

Latin Symbols		
Symbol	Unit	Name
\dot{Q}	W	Thermal power
c_p	kJ/kgK	Specific heat capacity at constant pressure
T	K	Temperature
P	W	Electrical power
<i>RTE</i>	-	Roundtrip efficiency
<i>COP</i>	-	Coefficient of Performance

Subscripts		
Symbol		Name
c		Cold
ch		Charging process

dc		Discharging process
eff		Effective
export		Export
h		Hot
HE		Heat engine
hh		„Hot“ hot storage temperature
imb		Imbalance
L		Lorentz
oi-adj		Operation imbalance adjusted
r		Return
s		Supply
theor		Theoretical

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