

ADVANCED ORGANIC RANKINE CYCLES FOR THERMALLY INTEGRATED CARNOT BATTERIES

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ABSTRACT

Carnot batteries are an emerging technology for base-load capable, electrical energy storage. During charging, the concept converts surplus electrical energy into thermal energy by means of a heat pump. During the discharge phase, a power cycle transforms the stored thermal energy back to electrical energy. Carnot batteries based on organic Rankine cycles rely on technically mature components and allow an effective integration of low-temperature heat sources to reach considerable efficiencies. However, thermally integrated Carnot batteries are stuck in a tradeoff between power-to-power efficiency, storage size and heat source utilization. This study suggests two approaches to minimize this trilemma. The first option targets at novel cycle layouts comprising flash cycles. Simulation results indicate that organic flash cycles with a two-phase expander increase the efficiency of Carnot batteries, particularly for high storage temperature spreads which enables more compact storages. The second option suggests Carnot batteries as highly integrated link between renewable power and district heating grids. That allows Carnot batteries to become a flexible sector coupling technology which can store and provide power and heat on demand.

1 INTRODUCTION

As renewable energy sources continuously substitute fossil fuels, the demand for energy storage technologies increases. The balancing of the daily mismatch between production and demand requires base-load capable storages which are able to shift the energy for several hours a day in a large scale. Today, pumped hydro storages represent around 99% of grid-scale electrical energy storages worldwide (Barbour *et al.*, 2016). However, their further extension is strongly limited by geographical limitations. In recent years, thermo-electrical energy storage gained attraction within the scientific community. Such storage technologies are often referred to as Pumped Thermal Energy Storage (PTES) or the broader term Carnot battery. Carnot batteries offer site-independent energy storage in variable power and capacity ranges (Dumont *et al.*, 2020). As Figure 1 shows, they consist of a power-to-heat cycle for charging (electrical heating, heat pump, reversed Brayton cycle) and a heat-to-power cycle for discharging (Rankine cycle, Brayton cycle). Between the cycles, a heat storage buffers the thermal energy. Molten salts or packed beds are used for high temperature storages, while hot water storages are often proposed for storage temperatures below 200°C (Steinmann *et al.*, 2019). These storage mediums allow a simple and cheap upscale of the storage capacity, thus the costs for Carnot batteries are mainly determined by the machinery. As the charging and discharging cycles require similar components, a reversible utilization of heat exchangers and expander/compressor can further reduce costs and improve compactness.

The major drawback of Carnot batteries compared to electro-chemical batteries is a low power-to-power efficiency of typically less than 70% (Dumont *et al.*, 2020). Therefore, several researchers propose the integration of low-grade heat to yield feasible efficiencies (Staub *et al.*, 2018; Eppinger *et al.*, 2021;

Dumont and Lemort, 2020). Such a thermal integration becomes particularly effective in Carnot batteries with low operating temperatures based on heat pump and organic Rankine cycles (ORC) (Frate *et al.*, 2020b). In contrast to other Carnot battery concepts, components for heat pumps and ORCs are readily available. Depending on the temperature levels and the ratio between waste heat and electrical energy, power-to-power efficiencies up to 100% and beyond are achievable. Thermal integration is not just an efficiency boost but also enables sector coupling as the Carnot battery becomes a flexible power/heat-to-heat-to-power/heat (or even cold) system. This feature offers applications where other storage technologies, e.g. lithium batteries, cannot compete.

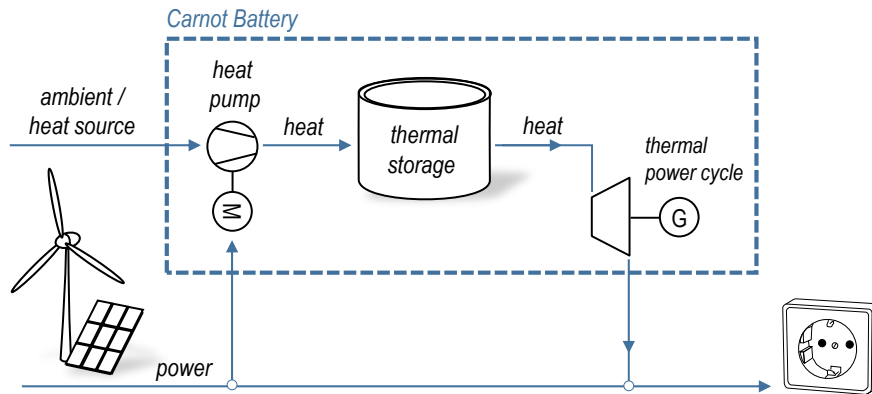


Figure 1: General scheme of a Carnot battery for electrical energy storage

However, thermally integrated Carnot batteries based on ORCs are naturally stuck in a trilemma between power-to-power efficiency, storage size and heat source utilization. The following section explains the thermodynamics behind the three dimensions of the trilemma. Afterwards, this paper will show two paths to overcome or minimize this fundamental optimization problem. The first option targets at advanced cycle configurations in terms of flash cycles without inadequately increasing the system complexity. The second option aims at highly integrated sector coupling by means of Carnot batteries in renewable power and district heating grids. The overall goal is to evaluate the potential of ORC-based Carnot batteries as an integrated storage technology for future energy systems.

2 THE CARNOT BATTERY TRILEMMA

Similar to most technical systems, more than one objective must be considered in the design process of Carnot batteries (Steger *et al.*, 2020). The most obvious performance indicator is the power-to-power efficiency η_{PTP} described in equation (1). It contains the efficiencies of the underlying sub-processes, i.e. coefficient of performance of the heat pump COP_{hp} and thermal efficiency of the ORC η_{orc} . Thermal storage losses would further decrease the efficiency but are neglected within this paper as they strongly depend on storage time, insulation and ambient conditions.

$$\eta_{PTP} = \frac{E_{out}}{E_{in}} = \frac{\int P_{el,orc} d\tau}{\int P_{el,hp} d\tau} = \frac{\eta_{orc} \cdot Q_{st}}{Q_{st}/COP_{hp}} = COP_{hp} \cdot \eta_{orc} \quad (1)$$

The volumetric storage capacity $E_{st,vol}$ in equation (2) displays the second key figure. $E_{st,vol}$ relates the stored energy that can be transformed back to electrical energy E_{out} to the storage volume V_{st} . Thus, $E_{st,vol}$ describes the storage density and indicates the compactness of the storage.

$$E_{st,vol} = \frac{E_{out}}{V_{st}} = \rho_{st} \cdot \bar{c}_p \cdot \Delta T_{st} \cdot \eta_{orc} \quad (2)$$

Carnot battery literature normally neglects the optional heat source supplying the heat pump in the definition of the power-to-power efficiency as the heat is considered a low-grade, otherwise wasted,

heat. However, this definition is only fully applicable if there is no alternative use or the heat supply forms a closed loop (Braumakis and Karellas, 2017). In this case, an intermediate fluid cycle typically transfers the heat, e.g. from solar panels, cooling applications or biomass combustion. When the heat comes from an open loop finite heat source as it is typical for industrial waste heat or geothermal brines, the heat source utilization represents a third parameter to be maximized. As thermally integrated Carnot batteries operate with heat and power, an exergy efficiency allows to take into account both, thermal and electrical energy (Frate *et al.*, 2020a). Equation (3) defines the exergy efficiency η_{II} for Carnot batteries. While the exergy of ORC Ex_{orc} and heat pump Ex_{hp} equal the electrical input and output from equation (1), equation (4) shows the expression for the heat source exergy. When no waste heat is available to supply the heat pump, the formula equals the PTP efficiency in equation (1).

$$\eta_{II} = \frac{Ex_{orc}}{Ex_{hp} + Ex_{hs}} \quad (3)$$

$$Ex_{hs} = \dot{m}_{hs} \cdot [h_{hs,in} - h_{hs,0} - T_0 (s_{hs,in} - s_{hs,0})] \cdot \tau \quad (4)$$

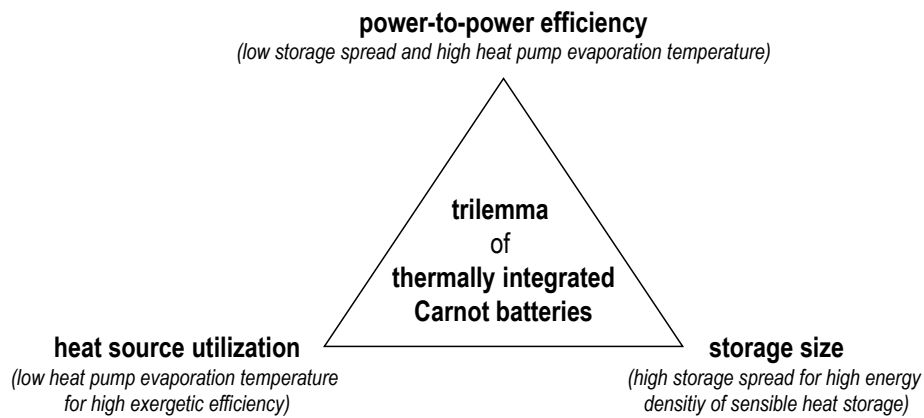


Figure 2: The trilemma of thermally integrated Carnot batteries

Figure 2 illustrates the trilemma of thermally integrated Carnot batteries based on heat pump – ORC systems between PTP efficiency, storage size and heat source utilization. A low storage temperature spread and a high heat pump evaporation temperature increase the PTP efficiency. However, the storage volume increases for a low storage spread and the heat source utilization is poor for a high heat pump evaporation temperature. Therefore, one objective can only increase at the cost of the others. Literature proposes multi-objective optimization approaches in order to point out a range of optimal compromises (Steger *et al.*, 2020; Frate *et al.*, 2020a). More complex processes, e.g. with multi-stage cycles or several sensible and latent heat storages, could shift these boundaries to higher values. However, an increasing complexity usually implies additional components and costs. Those higher costs are often not feasible from an economic point of view as thermally integrated Carnot batteries are typically proposed in a scale between 1-1000 kW where simple and cost-effective process designs are needed. The required thermal input limits the scale of Carnot batteries as it is several times larger than the electrical input (Frate *et al.*, 2020b). Thus, economic feasibility can be considered as a fourth dimension of the trilemma.

3 PROCESS DESIGNS

One option to improve the overall performance of Carnot batteries are advanced process design, e.g. organic flash cycles, without increasing the complexity inadequately. Figure 3 schematically shows the ORC and organic flash cycle processes in a Carnot battery. The investigated processes use a sensible hot water storage with a storage temperature up to 150°C. The working fluid is R245fa. Table 1 summarizes the boundary conditions for the simulations. A recuperated heat pump process charges the storage for all systems as there is no reversible counterpart to the flash separation.

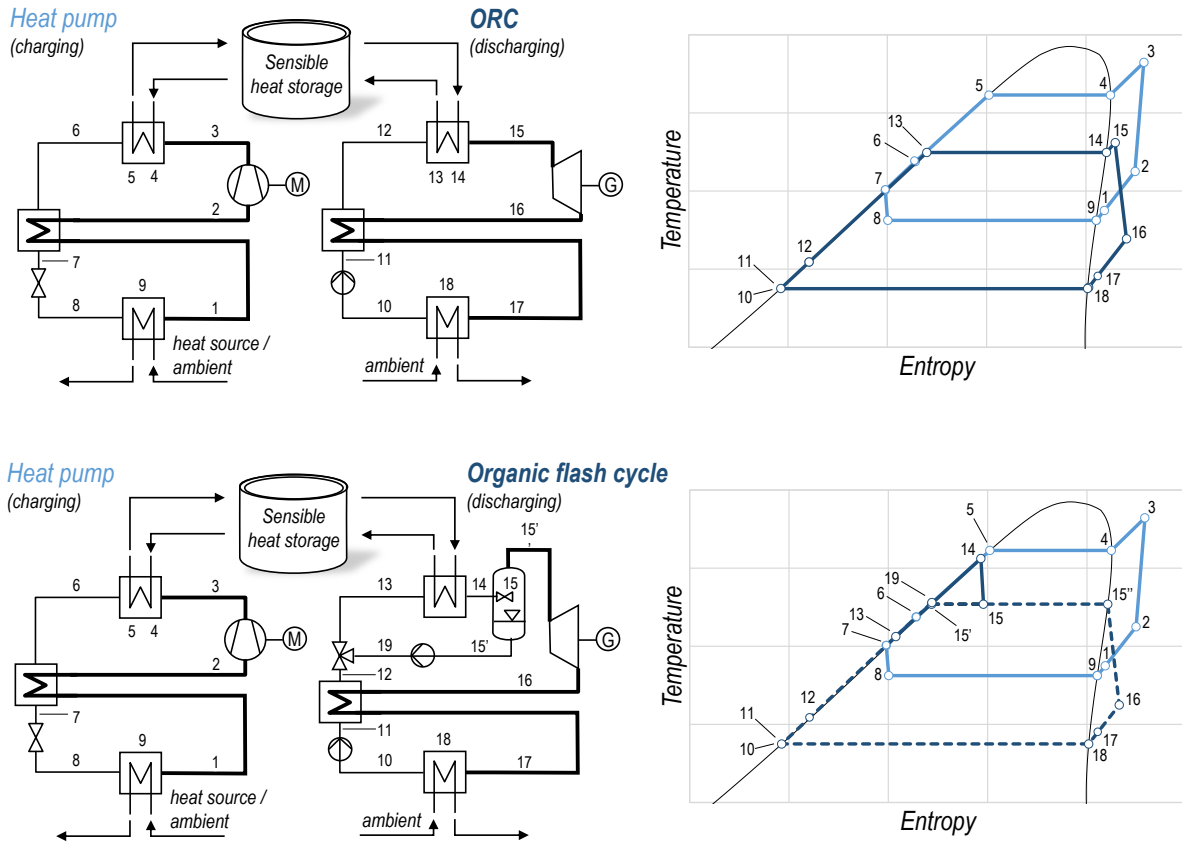


Figure 3: Flow schemes and T-s diagrams of Carnot batteries based on an ORC and an OFC (dotted lines indicate partial streams)

Table 1: Boundary conditions for the process simulation

Full name	Symbol	Value	Full name	Symbol	Value
Heat source temperature	t_{hs}	60-90°C	Pressure losses (neglected)	Δp	0 Pa
ORC condensation temperature	$t_{cond,orc}$	30°C	Storage efficiency	η_{st}	1
Max. upper storage temperature	$t_{st,max}$	150°C	Compressor efficiency	$\eta_{s,comp}$	0.80
Min. lower storage temperature	$t_{st,min}$	t_{hs}	Expander efficiency	$\eta_{s,exp}$	0.80
Pinch point heat exchangers	T_{pp}	5 K	Two-phase exp. efficiency	$\eta_{s,2PE}$	0.70
Min. superheating evaporators	T_{sup}	5 K	Pump efficiency	$\eta_{s,pump}$	0.80
Min. subcooling condensers	T_{sub}	5 K	El. efficiency machinery	η_{el}	0.95

3.1 Organic Rankine Cycle

A subcritical, recuperated ORC serves as benchmark for the simulations. For example Staub *et al.*, 2018 and Eppinger *et al.*, 2021 described such a system in detail. Subcritical cycles benefit most from thermal integration. Due to fixed upper and lower storage temperatures, the internal recuperator fully contributes to the cycle efficiency.

3.2 Organic Flash Cycle

Flash cycles originate from geothermal applications where a liquid brine is throttled and partially evaporated in a flash tank. Ho *et al.*, 2012 first transferred that principle to organic working fluids and introduced the organic flash cycle (OFC) as an alternative for ORCs in heat recovery applications. Since then, numerous advancements have been proposed to the OFC in literature (Lecompte *et al.*, 2015). In contrast to the ORC, the working fluid in the OFC does not evaporate during heat transfer. Instead, the saturated liquid fluid is throttled in a flash tank. The resulting vaporous fraction feeds an expander while the liquid fraction flows back to the heat exchanger. Thus, the non-isothermal heat transfer improves the temperature match between storage fluid and working fluid and reduces exergy losses.

3.3 Organic Flash Cycle with two-phase expander

Replacing the throttling valve with a two-phase expander (2PE) further reduces exergy losses and instead generates additional power during the flash step. A Carnot battery based on an OFC allows to take double advantage of a two-phase expander. The 2PE can replace the throttling valve in the OFC as well as the throttling valve in the heat pump cycle. Especially volumetric expanders can handle two-phase expansion (Dumont *et al.*, 2019). In an experimental study, Smith *et al.*, 1996 reached an isentropic efficiency of more than 0.70 in the two-phase region with a 25 kW twin-screw expander, expecting up to 0.80 in the megawatt range.

4 SIMULATION RESULTS

The simulations were conducted with the cycle simulation software IPSEpro 7.0 coupled with the Refprop fluid database. Figure 4 shows COP, ORC/OFC efficiency and PTP efficiency for Carnot batteries based on ORC, OFC and OFC with 2PE for different heat source and storage temperatures.

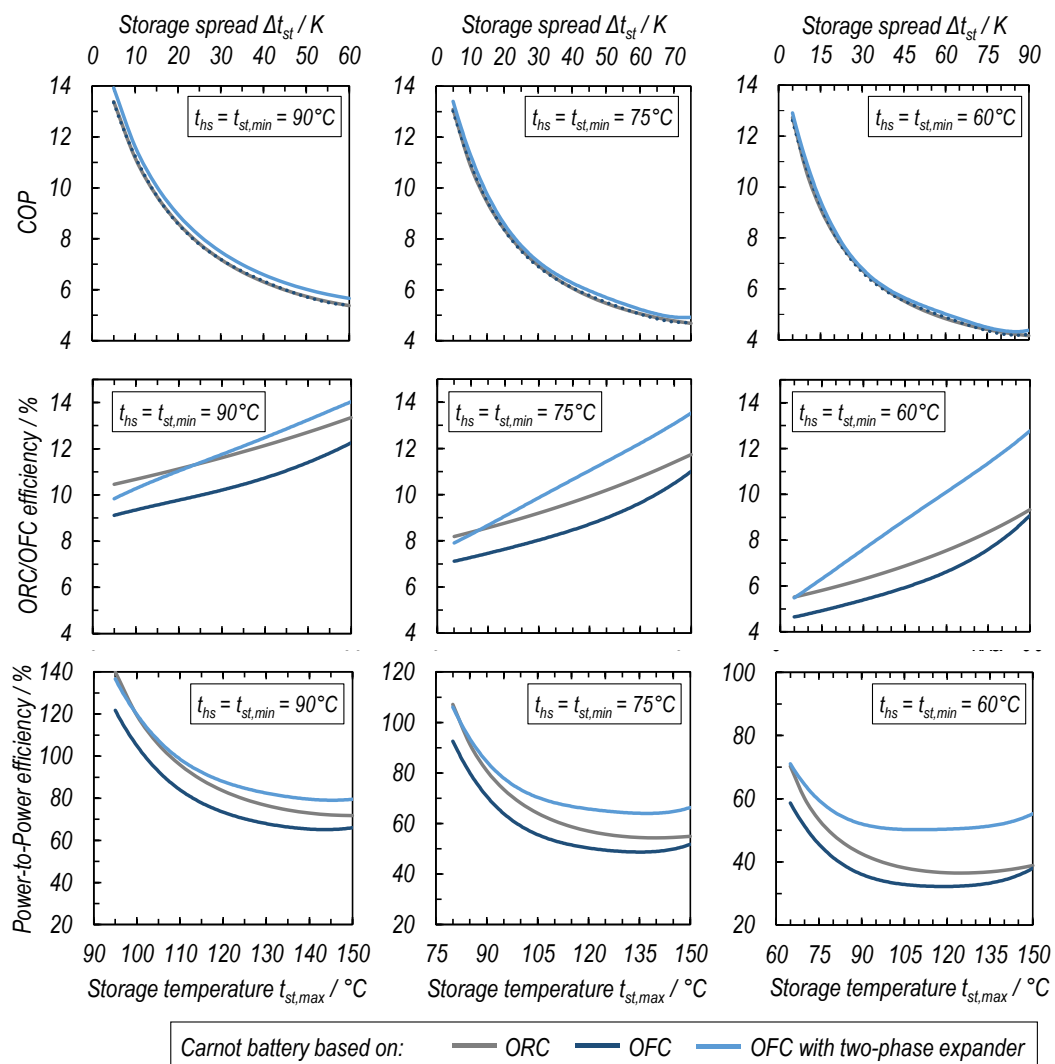


Figure 4: COP, ORC/OFC efficiency and PTP efficiency of the three investigated cycles at different heat source and storage temperatures

The COP in the cases of ORC and OFC is identical as they both use the same heat pump cycle. Generally, the COP decreases with increasing storage temperature and decreasing heat source temperature. The two-phase expander slightly improves the COP by 0.28-0.54 for $t_{hs} = 90^\circ\text{C}$ and 0.14-0.30 for $t_{hs} = 60^\circ\text{C}$. Contrarily, the ORC and OFC efficiency rise with an increasing storage temperature.

The ORC shows a better efficiency than the OFC for all cases, although the difference declines with increasing storage spread. The throttling losses of the OFC outweigh the advantageous non-isothermal heat transfer. However, an additional two-phase expander boosts the OFC efficiency by 0.69-1.78 percentage points (7.5-14.5%) for $t_{hs} = 90^\circ\text{C}$ and 0.86-3.67 percentage points (18.5-40.4%) for $t_{hs} = 60^\circ\text{C}$ compared to the basic OFC. The efficiency of the OFC with 2PE indicates a breaking point with the ORC. Above a certain storage temperature and storage spread, the OFC with 2PE becomes more efficient.

The PTP efficiency shows an overlapping effect as it generally decreases with increasing storage temperature and indicates a specific minimum. For a heat source temperature of 90°C , the PTP efficiency can reach values of more than 100%. The OFC generally performs poorer than the ORC. However, the OFC with two-phase expander outperforms the ORC for nearly all operating points. While both, ORC and OFC with 2PE, reach comparable PTP efficiencies for low storage spreads, the gap increases with increasing storage spread. At maximal storage spread (storage temperature 150°C), the OFC with 2PE yields 7.6, 11.1 and 16.1 percentage points (9.6%, 16.9%, 29.4%) higher PTP efficiencies for heat source temperatures of 90°C , 75°C and 60°C compared to the ORC. Thus, the OFC with 2PE becomes particularly interesting for moderate heat source temperatures and sensible storages with higher storage spreads which enables more compact storages at considerable PTP efficiencies.

5 HIGHLY INTEGRATED SECTOR COUPLING

Heat and surplus electrical energy need to be available simultaneously for thermally integrated Carnot batteries. Additionally, the required heat input is several times larger than the electrical input. That issue becomes difficult when thermally integrated Carnot batteries are directly linked to one heat source, e.g. an industrial waste heat source. The heat either needs to be buffered in large additional storage tanks or is wasted in times of no charging. In order to avoid poor heat source utilization and vanish the problem of heat availability, the decentral integration of thermally integrated Carnot batteries into district heating grids bridges the gap between heat and power and allows flexible sector coupling. That enables such systems to transform more power to heat or heat to power, depending on availability and demand (Steinmann *et al.*, 2019). Thereby, the scope of applications is expanded from purely electrical storage to heat and power management. Smart district heating grids will rely on solar, geothermal and industrial heat as well as biomass and synthetic gas. Short term and seasonal heat storages enable renewable heating throughout the year. Carnot batteries could substitute inefficient direct electrical heating in times of surplus electrical energy and allow back-transformation to electrical and thermal energy. During discharging, Carnot batteries can either maximize power production by rejecting heat to the ambient, directly provide heat at the condenser side or increase the return temperature of a heating grid (Jockenhöfer *et al.*, 2018). Thus, distributed mid-scale Carnot batteries could ideally support decentral, renewable microgrids. Figure 5 schematically shows such an integrated system (left) and indicates PTP efficiencies for various feed (heat source) and return (heat sink) temperatures of a heating grid.

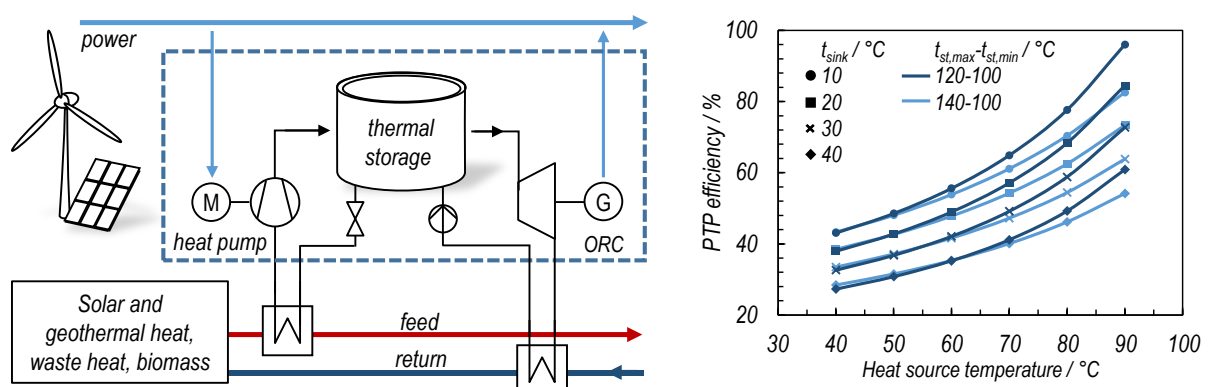


Figure 5: Integrated ORC-based Carnot battery within district heating grid (left); PTP efficiency depending on heat source, heat sink and storage temperatures (right)

6 CONCLUSION AND OUTLOOK

Electrical energy storage in terms of Carnot batteries offers a promising base-load capable storage option for renewable energy systems. The present paper focuses on Carnot batteries based on organic Rankine cycles utilizing heat sources (thermal integration). First, the trilemma of thermally integrated Carnot batteries is introduced as a tradeoff between power-to-power efficiency, storage size and heat source utilization. Two approaches to minimize this trilemma are presented. The first option proposes organic flash cycles as an alternative for organic Rankine cycles. Simulations indicate that throttling losses in the OFC vanish the advantage of non-isothermal heat transfer. However, a two-phase expander could replace the throttling valves in both modes, OFC and heat pump. The OFC with two-phase expander reaches comparable efficiencies for low storage spreads but clearly outperforms the ORC with increasing storage spread. Thus, OFC with two-phase expansion yields higher PTP efficiencies at reduced storage sizes, enabling more compact storages. Besides, linking renewable power and district heating grids by means of Carnot batteries allows to flexibly store and provide power and heat on demand. This facilitates new applications, e.g. sector coupling in renewable micro-grids, where other storage technologies cannot compete. In order to implement flexible Carnot batteries into energy grids, the dynamics and off-design behavior require further investigation and advancements. Additionally, the proposed concepts with flash cycles strive for the development and experimental validation of two-phase expanders.

NOMENCLATURE

c_p	specific heat capacity	(kJ/kg K)	Subscript	
E	electrical energy	(kJ)	0	ambient
Ex	exergy	(kJ)	el	electrical
h	specific enthalpy	(kJ/kg)	in	input
p	pressure	(Pa)	hp	heat pump
P	electrical power	(kW)	hs	heat source
Q	thermal energy	(kJ)	max	maximum
s	specific entropy	(kJ/kg K)	min	minimum
t	temperature	(°C)	out	output
T	absolute temperature	(K)	st	storage
V	volume	(m ³)	vol	volumetric
η	efficiency	(%)		
ρ	density	(kg/m ³)		
τ	time	(s)		
2PE	two-phase expander			
COP	coefficient of performance			
ORC	Organic Rankine Cycle			
OFC	Organic Flash Cycle			
PTES	Pumped Thermal Energy Storage			
PTP	power-to-power			

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