David Tomás Sánchez Martínez
Lourdes García Rodríguez
(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

Editorial Universidad de Sevilla

Proceedings of the 7th International Seminar on

ORC

Power Systems

David Tomás Sánchez Martínez
Lourdes García Rodríguez
(coordinadores)

Proceedings of the 7th International Seminar on

ORC Power Systems

(ORC2023)

4th to 6th
SEPTEMBER
SEVILLE 2023

EDITORIAL UNIVERSIDAD DE SEVILLA

Sevilla, 2024

Colección Actas
Núm.: 91

ISBN 978-84-472-2745-7
DOI: https://dx.doi.org/10.12795/9788447227457

Diseño de cubierta y maquetación: los autores

INDEX OF CONTRIBUTIONS

SEVILLE 2023
7th International Seminar on O.R.C. Power Systems

DOI: https://dx.doi.org/10.12795/9788447227457_33

Pareto front analysis for the design and the working fluid selection in ORC-based pumped thermal energy storage technology in both pure electric and cogenerative applications

Marco Astolfi[1,*], Dario Alfani[1], Andrea Giostri[1]

[1] *Dipartimento di Energia, Politecnico di Milano, Via Lambruschini 4a, 20156, Milano (MI), Italy*

*Corresponding Author: marco.astolfi@polimi.it

ABSTRACT

Carnot Batteries are a sub-technology of Pumped Thermal Energy Storage concept where closed cycles are used in both charging and discharging phase. In charging mode, cheap off-peak electricity from the grid is used to store heat at a temperature different than the ambient one (generally higher) while in discharging mode the stored heat is exploited for power production. Carnot Batteries can be designed with different thermodynamic cycles (Brayton cycle, Steam Rankine cycle, Organic Rankine cycle) and can adopt different types of thermal energy storage technologies. For low duration storage (daily or weekly cycling) sensible or latent energy storage with phase change materials can be adopted, while for long duration storage (months, seasonal) the use of thermochemical reactions could be a valid option, as proposed by H2020 RESTORE project. Performance of Carnot Batteries is highly affected by the thermal storage temperature, the condensation temperature in discharging mode and the availability of residual heat at a temperature higher than the ambient one for boosting the heat pump coefficient of performance in charging cycle. This paper focuses on the optimal design of a reversible thermodynamic system working as a heat pump (HP) cycle in charging mode and as an organic Rankine cycle (ORC) in discharging mode. A dedicated numerical model developed in Python is employed to compare the techno-economic performances of different working fluids and select the most promising candidates. Main difficulty is related to the use of reversible heat exchangers which design impacts both on the charging and discharging operation, strongly affecting the system round trip efficiency, and requiring a discretized off-design modelling. A Pareto front of optimal round trip efficiency against total area of heat exchangers is obtained by varying the main design parameters, such as heat transfer temperature differences and heat exchangers pressure drops. Results show that for a given overall heat transfer area low critical temperature fluid are mainly penalized by poor HP performance due to high compressor specific work, while high critical temperature fluids are mostly penalized by high pressure drops caused by the low fluid density. The most promising working fluid for the present application is cyclopentane, reaching a RTE close to 35% for the pure electric configuration at its maximum RTE over total heat transfer area parameter.

1 INTRODUCTION – ENERGY STORAGE TECHNOLOGIES

In order to reach a full decarbonization of the electricity market a massive adoption of renewable energies will be required in the soon future and those technologies will need to be coupled to energy storage in order to compensate for their non-fully predictable and non-programmable power output. Energy storage technologies are numerous and cover a large range in power and capacity (namely storage duration): from few kW to multi-MW, from few seconds to seasonal storage. Some energy storage technologies are already at commercial level like flywheels, electrochemical batteries and pumped hydro energy storage, having a high penetration on the market in spite of some intrinsic limits. As a consequence, the energy market strongly needs alternative solutions that can provide energy storage in a reliable, efficient, site independent and affordable way, possibility pushing the storage duration towards long term (monthly, seasonal). Several technologies have been proposed in recent years in open literature or developed by startups and large companies to answer to these needs, leading to a variety of concepts that can be basically split in three main categories: mechanical storage, pumped thermal energy storage and chemical energy storage. Technologies based on thermodynamic systems are numerous and they may require both the pressurization of a fluid and the storage of heat: among them adiabatic compressed air energy storage (A-CAES) (Cheung, Carriveau, & Ting, 2012), CO_2 Battery (Astolfi, Rizzi, Macchi, & Spadacini, 2021) and liquid air energy storage (LAES) are the most mature ones but they all require not only the accumulation of energy in a sensible or latent energy storage, but also the storage of the working fluid at high pressure and, in case air is not used, also at low pressure. Carnot battery technologies, on the contrary, are based on the adoption of closed thermodynamic cycles in both charging phase (heat pump for heat temperature upgrade) and discharging phase (heat exploitation with a power cycle) and thus they require only the storage of heat, potentially simplifying the system design and operation, and reducing the size for seasonal storage. Finally, Carnot batteries performance can be increased by exploiting waste heat recovery in the charging phase by increasing the evaporation temperature of the heat pump and thus the Coefficient of Performance (COP). Carnot batteries are differentiated by the selection of the thermodynamic cycle adopted for charging and discharging phase and the type of thermal energy storage adopted:

- **Thermodynamic cycle:** the use of different thermodynamic cycles is proposed in literature and on the market: (i) closed gas Brayton cycles are commercialized by Malta Inc. (Laughlin, 2017) and also studied by SWRI, (ii) Steam Rankine cycles have been proposed by H2020 CHESTER project (Steinmann, 2014), (iii) Organic Rankine Cycles (ORC) are investigated by H2020 CHESTER (Steinmann, 2014) and RESTORE projects (Alfani, Giostri, & Astolfi, 2023) while transcritical CO_2 cycles are proposed by Man Energy Solution and Echogen (Miller, 2018). Additionally, some systems architectures do not adopt a heat pump for the charging cycle preferring to directly dissipate electrical power to the HTF medium, usually air, and eventually to rocks as proposed by Siemens Gamesa (Eggers, von der Heyde, Thaele, Niemeyer, & Borowitz, 2022), Pintail power and Enel Green Power in cooperation with Brenmiller Energy.
- **Thermal storage**: thermal storage can be classified in (i) sensible heat storage, in case liquid or gas streams are heated during the charging phase and then stored directly or by releasing heat to a high heat capacity medium, like in dual media thermocline solutions (rocks, metal spheres), (ii) latent heat storage, in case the heat is used in charging phase for melting a solid or vaporizing a liquid storage medium called Phase Change Material (PCM) (ice for low temperature storage, salts and their eutectic mixtures for temperatures up to 700-800°C (Sarbu & Dorca, 2019)) and (iii) thermochemical storage, where the heat is used to support a specific chemical reaction. Latent and thermochemical energy storage are mainly proposed for thermodynamic cycles with a pure working fluid phase transition (i.e., evaporation and condensation of organic fluids or CO_2), while sensible heat is preferrable for Brayton cycles, supercritical CO_2 or non-eutectic fluid mixtures, thanks to better matching of the temperature profiles.

2 LITERATURE ON CARNOT BATTERIES AND SCOPE OF THE STUDY

Previous studies have already shown the potential of ORC-based PTES systems considering both decoupled and coupled cycles architectures and, in this latter case, scientific literature has mostly focused on small-size systems that allow for the adoption of volumetric machines working as compressors in charge operation and expanders during discharge. Steger et al. (Steger et al., 2020) carried out a numerical multi-objective (electrical storage capacity and power-to-power efficiency) Pareto optimization to provide insights on the design and working fluid selection of a reversible HP/ORC system coupled to a latent energy storage. In particular, the authors highlighted the relevance of the working fluid enthalpy of vaporization in the process design, as it directly affects the mass flow rate and thus it significantly influences the investment costs of the system. Studying a similar system and considering the same working fluids (cyclopentane, R1233zd(E), Novec649 and R365mfc), Eppinger et al. (Eppinger, Zigan, Karl, & Will, 2020) achieved power-to-power efficiencies above 60% for a heat source of 110°C, adopting both a sensible and latent heat storage for a pure electric system. The authors performed several parametric analyses and highlighted that, for most of the investigated cases, R1233zd(E) appeared to be the best choice thanks to the trade-off between system efficiency and environmental sustainability and safety. On the other hand, when considering also latent storages solutions, cyclopentane achieved the highest power-to-power efficiency. Limiting their analysis to reversible systems coupled to a sensible heat storage, Dumont et al. (Dumont & Lemort, 2020) developed a set of performance maps considering different combinations of working fluid, waste heat temperatures (50-90°C), storage temperature glide (5-15°C), and ambient temperature (0-40°C). The authors identified R1233zd(e), R1234yf, R11, R236ea and R245fa as the working fluids presenting the best performances. In the framework of the H2020 CHESTER project, Jockenhöfer et al. (Jockenhöfer, Steinmann, & Bauer, 2018) investigated a decoupled system adopting butene for both the charging and discharging cycles. The results of the analysis showed that the investigated system can provide a net power ratio of 1.25 if a heat source temperature of 100°C and a heat sink temperature of 15°C are available. A similar system has been studied by Frate et al. (Frate, Antonelli, & Desideri, 2017) investigating 17 working fluid candidates but limiting the analysis to a sensible heat storage. The numerical results showed the possibility to boost the round trip efficiency (RTE) to values higher than 1 thanks to the combination with a low-grade heat source. Considering a heat source temperature of 110°C, R1233zd(E) has been identified as the optimal fluid as it allows to achieve a theoretical maximum RTE of 1.3. Finally, the H2020 RESTORE project (Alfani et al., 2023) is focusing on the design of a seasonal storage system for district heating (DH) purposes that adopts ORC-based Carnot batteries to support an endothermic (during charging process) and exothermic (during discharging process) thermochemical reaction that would allow to store energy by mean of solids salts with high energy densities, requiring low-cost storage technologies already used in food and chemical industry.

This paper aims to discuss the methodology proposed for the selection of the best working fluid(s) for Carnot battery applications adopting coupled cycles that use the same working fluid and the same heat exchangers in both operation modes as reported in Figure 1 with representative T-s diagrams. Differently to other works in literature, two different turbomachines are adopted for the compression and the expansion of the working fluid since the use of reversible volumetric machines (piston, screw or scroll) is still characterized by very uncertain information about the penalization due to volume ratio variation when passing from one to another operation mode. From one hand, the choice of using coupled cycles is well motivated by the possibility to reduce the investment cost, ensuring high annual utilization factors of main components (i.e., heat transfer equipment) and facilitate the charging and discharging operations of the thermal energy storage using both solid-to-liquid PCM and thermochemical reactors. On the other hand, using coupled cycles requires specific numerical tools to account for the heat exchangers operation in off-design mode and precisely evaluate the impact on discharge cycle performance when pressure levels and mass flow rates different from the charging cycle are adopted.
In this study a subcritical heat pump (HP) and subcritical power cycle (PC), adopting an organic working fluid, are considered in order to provide the best matching between the fluid phase transition process and both latent or thermochemical thermal energy storages that can be implemented in this concept. Two different cases have been considered: (i) a electricity-only (ELE) storage system, which operates with daily or weekly cycles of charging and discharging and aims at maximizing the electrical round trip efficiency, adopting a latent thermal energy storage for heat accumulation at high temperature as proposed by H2020 CHESTER project; (ii) a cogenerative system (CHP) which main goal is dispatching large amount of thermal energy on seasonal base for district water heating through ORC condensation, while also providing dispatchability and storage of electricity as a secondary benefit; in this case a thermochemical reaction is at the base of the thermal energy storage as proposed by H2020 RESTORE project (Available online at: https://www.restore-dhc.eu/)

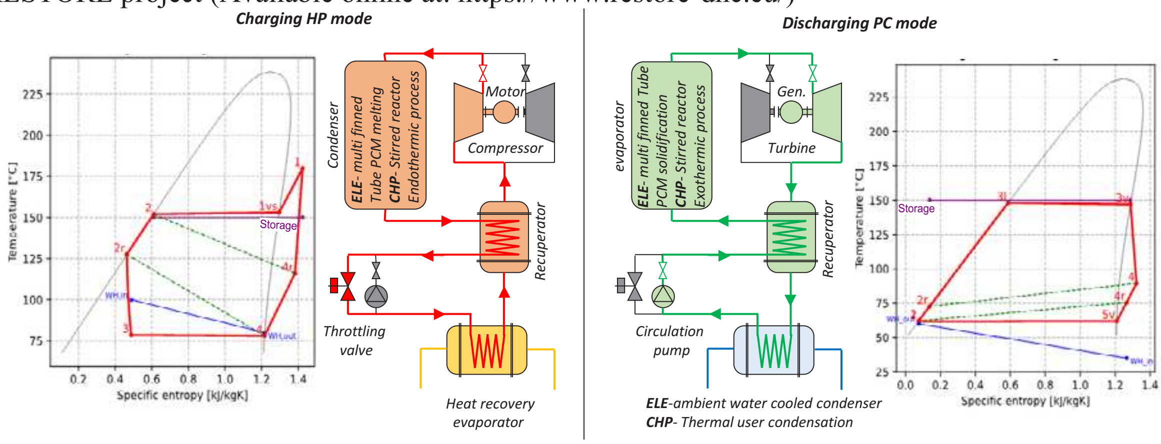

Figure 1: Coupled cycles configuration scheme adopting reversible heat exchangers and representative T-s diagrams.

3 METHODOLOGY

A numerical code is developed in Python 3.10 to compute the system overall round-trip efficiency (RTE), see Equation (1), and heat transfer area of all the heat exchangers for different combinations of working fluid and cycle operating parameters and it implements REFPROP 10 (Lemmon, Bell, Huber, & McLinden, 2018) for the computation of working fluid thermodynamic and transport properties. For the CHP case, it is possible to always obtain large thermal power released to the district heating network independently from the cycle configuration and the working fluid selected because of the rather low maximum achievable efficiency of the PC. For this reason, for both investigated cases electrical round-trip efficiency of the system, defined as the ratio between the net power released by the power cycle and the electrical power absorbed by the heat pump (according to the assumption of same charging and discharging hours), is selected as the main figure of merit to account for the system performance and to guide fluid selection. In this preliminary analysis, the additional auxiliaries consumption related to the cooling water circulation, to the waste heat or to the thermal energy storage are neglected for both the charging and discharging cycle. Thanks to this simplification the RTE is equivalent to the product between the heat pump coefficient of performance (COP_{HP}) and the power cycle electrical efficiency ($\eta_{,PC}$), as reported in Equation (1).

$$RTE = \frac{\dot{W}_{turb,el,PC} - \dot{W}_{pump,el,PC}}{\dot{W}_{comp,el,HP}} = COP_{HP} \cdot \eta_{PC} \quad (1)$$

From a general point of view, by adopting larger heat transfer surfaces it is possible to increase the system overall RTE thanks to the lower irreversibilities in the heat transfer processes, at the expenses of a higher heat exchanger investment cost that likely represent the main share of capital cost according to the high heat/electrical power ratio of the adopted thermodynamic cycles (high COP for the HP and low PC thermal efficiency). The trade-off between RTE and total heat transfer area is investigated with a Non-dominated Sorting Genetic Algorithm (NSGA) (Deb, Pratap, Agarwal, & Meyarivan, 2002) for multi-objective optimization to define the Pareto front and identify the most promising techno-economic solutions for both the ELE and the CHP cases. The optimization variables considered for this analysis are six design parameters that characterize the heat exchanger dimensions:

- The pinch point temperature differences (ΔT_{pp}) in the high-pressure (condenser in charge mode) and low-pressure (evaporator in charge mode) heat exchangers, which directly affect the heat transfer average temperature difference and thus the heat exchangers UA parameter. Once the storage temperature is assumed and the ΔT_{pp} defined, the minimum and maximum pressure of the charging cycle are also determined. The higher the ΔT_{pp}, the lower is the heat transfer area with a consequent penalization in performance because of the increased pressure difference in the HP cycle and the lower pressure ratio in the PC one. The pinch point temperature difference in the recuperator is not considered as optimization variable as it results from the specification of the compressor outlet temperature, which fixes the thermal duty of the recuperator. In a precedent study (Alfani et al., 2023) it has already been highlighted the dependency of the overall system RTE and heat transfer surfaces from the compressor outlet temperature, so in this work the outlet temperature from the compressor has been fixed at a conservative value of 180°C to limit de-superheating at compressor outlet, also considering that the actual limit of existing high-temperature heat pumps is close to 200°C (Turboden S.p.A., 2023).
- The pressure drops (Δp) on the working fluid side for all the heat exchangers of the system that affects the working fluid velocity in the tubes. Higher is a specific pressure drop, higher the heat transfer coefficient and lower the area of the heat exchanger for the same duty and average ΔT but also lower is the system performance due to additional compression ratio in charging and reduction of the expansion one in discharging.

The performance of the turbomachinery has been set constant independently of the working fluid choice, the pressure ratio and the volumetric flow rate thus assuming to design compressor and turbine as axial machines adopting a suitable number of stages and rotating at optimal speed (i.e. adopting gear box or power electronics for power output frequency control). Assumed efficiency values are 75%, 80% and 85% for the pump, the compressor and the turbine respectively.

Table 1: Heat pump cycle heat exchangers design parameters range for Pareto front analysis.

Parameter	Value
HP Evaporator pinch point temperature difference, °C	[0.5 - 10]
HP Condenser + de-superheating pinch point temperature difference, °C	[0.5 - 10]
HP Evaporator overall pressure drops working fluid side, %	[1% - 20%]
HP Condenser + de-superheating overall pressure drops working fluid side, %	[1% - 20%]
HP recuperator pressure drops working fluid low pressure side, %	[1% - 20%]
HP recuperator pressure drops working fluid high pressure side, %	[1% - 20%]

3.1 Heat exchangers preliminary sizing methodology

A realistic heat exchangers preliminary sizing is of high relevance for the study of coupled Carnot battery systems where the same heat exchangers are used in different modes (alternatively as condenser or evaporator) and at different pressure levels. Simplified methods adopting the same UA in both operation modes likely lead to misleading results as they do not take into account the changes in fluid thermophysical properties which lead to variations of fluid velocity, pressure drops and heat transfer coefficient. Heat exchanger design is carried out in the charging cycle calculation with the following methods and assuming tube diameter and tube thickness equal to 25 mm and 2 mm respectively, SS316 material and tube internal roughness equal to 10^{-3} mm:

- ***High pressure heat exchanger*****:** in charging mode fluid condensation and de-superheating are carried out in the coiled tubes of the stirred reactor acting as a once-through heat exchanger for the CHP case or in the tubes of the PCM heat exchanger for the ELE case. Inlet fluid velocity is determined in order to match the assumed overall pressure drop. Number of tubes is then calculated, and the tube length and overall heat transfer area are eventually retrieved knowing the local overall heat transfer coefficient obtained by the combination of internal heat transfer coefficient (working fluid side) and the external one (stirred reactor or PCM side), plus the metal conductive resistance. Gnielinski correlation (Gnielinski, 1975) is adopted for vapor working fluid de-superheating, Cavallini correlation (Cavallini et al., 2006) is implemented for condensation (requiring an additional internal iterative procedure for the determination of the tube wall temperature). Differently, the external heat transfer coefficient is assumed constant and equal to value of 2000 W/m^{2}K for both the stirred reactor as suggested from [34] and for a solid-liquid PCM (in this case local heat transfer coefficient is much lower with values around 100 W/m^{2}K (Castell et al., 2008) but finned tubes with high external to internal area ratio can be adopted (Asgari, Javidan, Nozari, Asgari, & Ganji, 2021; Zhu, Li, & Zhu, 2022)). Pressure drops are calculated only considering the frictional contribution for vapor and two-phase flow regime.
- ***Low pressure heat exchanger*****:** in charging mode the fluid evaporation is carried out in a shell and tube once-through heat exchanger and, also in this case, the number of tubes is found iteratively to match the assumed pressure drops while hot pressurized water from waste heat recovery or renewable energy flows in the shell. Liu and Winterton correlation (Liu & Winterton, 1991) is adopted for the heat transfer coefficient in flow boiling conditions (requiring an additional internal iterative procedure for the determination of the heat flux) while the external heat transfer coefficient is calculated with Zukauskas correlation (Žukauskas, 1972) by assuming a fixed longitudinal and transversal tube pitch (both equal to 1.25), a staggered tube arrangement and a fixed baffle spacing with respect to shell diameter (0.2). Working fluid pressure drops in evaporation are calculated only considering the frictional contribution. A co-current heat exchanger is adopted in order to increase the evaporation temperature and improve the COP as already discussed in (Alfani et al., 2023).
- ***Recuperator:*** a finned tube battery heat exchanger is implemented considering liquid fluid flowing in tubes and vapor flowing on the external finned surface in cross flow arrangement. The number of tubes and tube pitch calculation relies on an iterative procedure to match the pressure drops on liquid and vapor side, respectively. Gnielinski and Zukauskas correlations are used for the computation of liquid and vapor heat transfer coefficients, respectively. A fixed $A_{ext,tot}/A_{int}$ ratio equal to around 11 is adopted, as suggested in (Macchi & Astolfi, 2016).

When switching to power production mode the off-design operation of the heat exchangers is calculated fixing its geometry in order to find the cycle evaporation temperature, the condensation temperature and the recuperator outlet temperature plus all the pressure drops by adopting the correct correlation for each fluid state as reported above. The resolution scheme is reported in Figure 2.

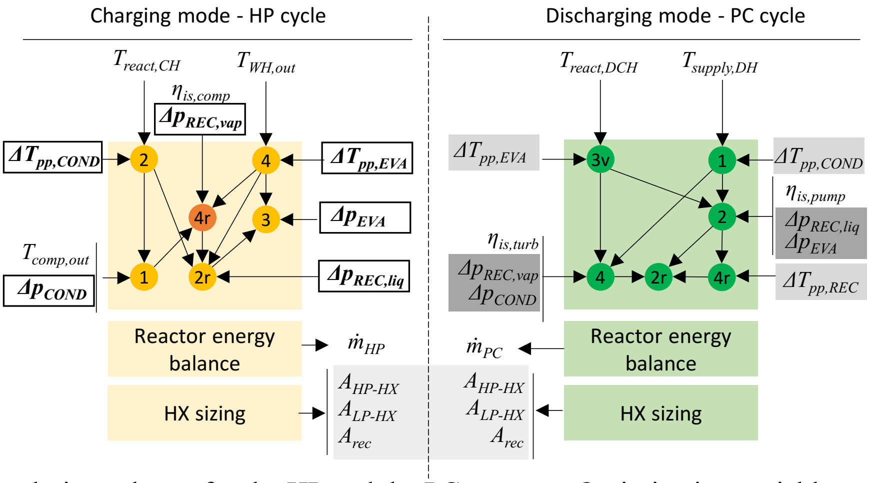

Figure 2: Resolution scheme for the HP and the PC systems. Optimization variables are in bold and white boxes on the HP cycle, closing variables used to match the heat exchangers surface are reported in light gray boxes on the PC cycle, while variables in dark gray box are iteratively calculated.

4 RESULTS

Results section is divided in two parts: the first one focuses on the analysis of the results obtained for cyclopentane with a description of the Pareto fronts and the trend of variables adopted in the analysis, the second part focuses on the comparison of cyclopentane with two other fluid candidates.

4.1 Cyclopentane analysis

The results of the multi-objective optimization are reported in Fig. 3 for both the electricity-only (ELE) configuration (Fig. 3.a) and the cogenerative (CHP) one (Fig. 3.b), considering cyclopentane as working fluid. The figure reports the tradeoff between electrical RTE (x-axis) and the total heat transfer surface of the system (y-axis): in blue it is depicted the overall population explored by the NSGA optimizer in the last generation, while in red it is possible to notice the optimal solutions on the Pareto front, i.e. the set of non-dominated solutions. 219

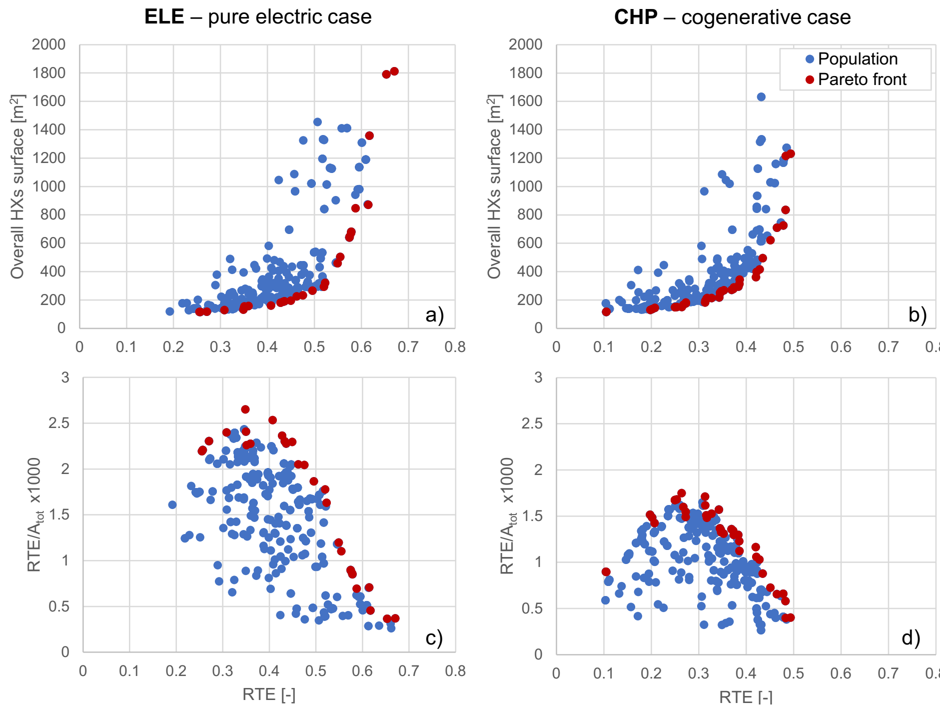

Figure 3: Pareto front of optimal solutions (red) for the electricity only (a) and cogenerative case(b). RTE/A_{tot} ratio for the electricity only (c) and cogenerative (d) cases.

As expected, the electricity only system is capable of achieving higher values of round-trip efficiency (up to close 70% that is value comparable to current Li-ion batteries and PHES) thanks to the much lower condenser pressure in the power cycle (discharging mode), which allows for a higher enthalpy drop in the turbine and thus an improved net power output of the system.
From the graph of Fig. 3.a and 3.b it is possible to notice that the trend of the overall heat transfer surface versus the electrical RTE of the system is strongly not linear: above a certain RTE threshold, an increase of the system performance can be attained only with an exponential growth of heat transfer surfaces due to the non-linear correlation between heat transfer temperature differences and heat transfer surfaces. This RTE threshold is equal to around 0.5 for the ELE configuration and to around 0.4 for the CHP system, as it is possible to notice from the evident soaring of heat exchangers surfaces above these values. It is also worth mentioning that the maximum RTE/A_{tot} (Fig. 3.c and 3.d) is not obtained by pushing the round-trip efficiency to the maximum achievable values and the optimal point is found for both cases in a region of the Pareto front characterized by rather low RTE values. In particular, the maximum RTE/A_{tot} is found between RTE values of 0.3 and 0.4 for the ELE configuration, while it is characterized by lower values (0.25-0.35) for the CHP system, as it could be expected due to the overall lower RTE values of such configuration. In addition, for the CHP system the RTE/A maximum value is lower than in the ELE case (-30%).

The trends of the Pareto optimal values for the pinch point temperature differences of the low-pressure heat exchanger (evaporator in HP mode) and of the high-pressure heat exchanger (condenser in HP mode) are depicted in Fig. 4.a and 4.b, respectively. For both system configurations the trend of these optimization variables is similar: the optimization variable which is mainly responsible for the trade-off between RTE and overall HX surface is the $\Delta T_{pp,LP}$, as this parameter linearly varies between the minimum and maximum RTE of both systems, being pushed to the lower bound only for combinations of very high RTE and HXs total surface. Similar considerations can be made for $\Delta T_{pp,HP}$, even if it possible to notice that the optimizer set its value really close to the upper bound in the low-RTE range of the Pareto front, denoting that it could be useful to slightly relax the upper bound on this variable.

These results also suggest that the assumption considered for the precedent analysis of using a pinch point temperature difference of 2°C to design the heat exchangers in the HP/charging cycle of the cogenerative system (Alfani et al., 2023) could be improved by adopting values around 5°C and 7°C for the LP HX and HP HX respectively, in order to attain the maximum RTE/A_{tot} ratio. 220

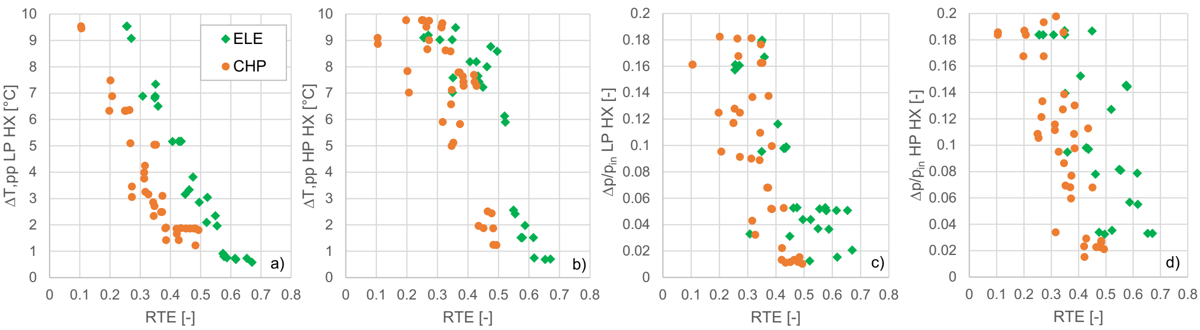

Figure 4: Trend of some of the optimization variables along the Pareto front for the electricity only (green) and cogenerative (orange) cases.

As the pressure drops affect less significantly the trade-off between system performance and overall HX surface, their trend on the Pareto front is less linear and tends to be more scattered. However, as expected, it is possible to notice that the working fluid side relative pressure drop in the low-pressure HX tends to decrease for higher RTE values. This trend can be explained considering that this pressure drop has two opposing effects on the HX surface as (i) higher fluid velocities lead to higher convective heat transfer coefficients and (ii) higher pressure drops in two-phase conditions (in this case evaporation), lead to lower average heat transfer temperature differences considering a fixed $\Delta T_{pp,LP}$. However, as the first effects is more significant than the second, the higher the LP HX pressure drop, the lower this heat exchanger surface. On the other hand, even if this variable does not affect the COP of the heat pump, as it only increases or decreases the pressure drop foreseen by the lamination valve, it strongly influences the condensation temperature of the power cycle, significantly affecting the power output attainable in discharge mode.

In contrast, the pressure drop in the cold and low-pressure side of the recuperator (heat pump mode) also affects the COP of the charge cycle as, at fixed compressor outlet temperature and pressure, it increases the compressor pressure ratio and thus its electrical consumption. For this reason, to maximize the COP of the heat pump the optimizer tends to select the optimal values of this variable closer to the lower bound.

4.2 Fluid comparison

Figure 5 depicts the comparison in both the ELE and CHP case of cyclopentane and the other two fluids, NOVEC649 (representative of fluids with a lower critical temperature) and octane (representative of fluids with a higher critical temperature). R1233zd(E), that is a fluid highly recommended in open literature for these applications, has not been included both because of its low critical temperature, likely too close to the storage temperature, and because if may be phase out in the next years according to the REACH regulation (Williams, Panko, & Paustenbach, 2009). It is possible to highlight that octane can potentially reach RTE slightly higher than cyclopentane especially in the CHP case, but this is generally obtained with heat exchangers with an overall heat transfer area that, for the same RTE, can be up to 60% higher in the interval of RTE where the maximum of RTE/A_{tot} is located. This aspect results from the larger ratio between the latent heat of vaporization and the enthalpy variation in compression/expansion, which is a consequence of the distance between the thermodynamic cycle and the fluid critical point, which leads to lower operative pressures thus requiring higher heat transfer surfaces to achieve reasonable pressure drops in the components. Only in some ELE cases at very high heat transfer area, octane can reach the same RTE with a lower heat transfer area. Additionally, the use of octane may lead to challenges in system operation related to the leakage in of air for sub-atmospheric condensation pressures and the very high volumetric flow rates at turbine outlet: this is particularly relevant for ELE case where the condensation pressure can be low as 0.03 bar. NOVEC649 analysis leads to almost opposite considerations: the proximity of the critical point implies a reduction of heat pump performance because of the lower latent heat of condensation at high temperature, which is not compensated by the compact heat exchangers that can be designed with higher operating pressures. RTE/A_{tot} parameter is penalized and generally reaches values up to half the corresponding value achievable with cyclopentane. Maximum reachable RTE are penalized as well and cannot go over 60% in ELE case and 50% in CHP one.

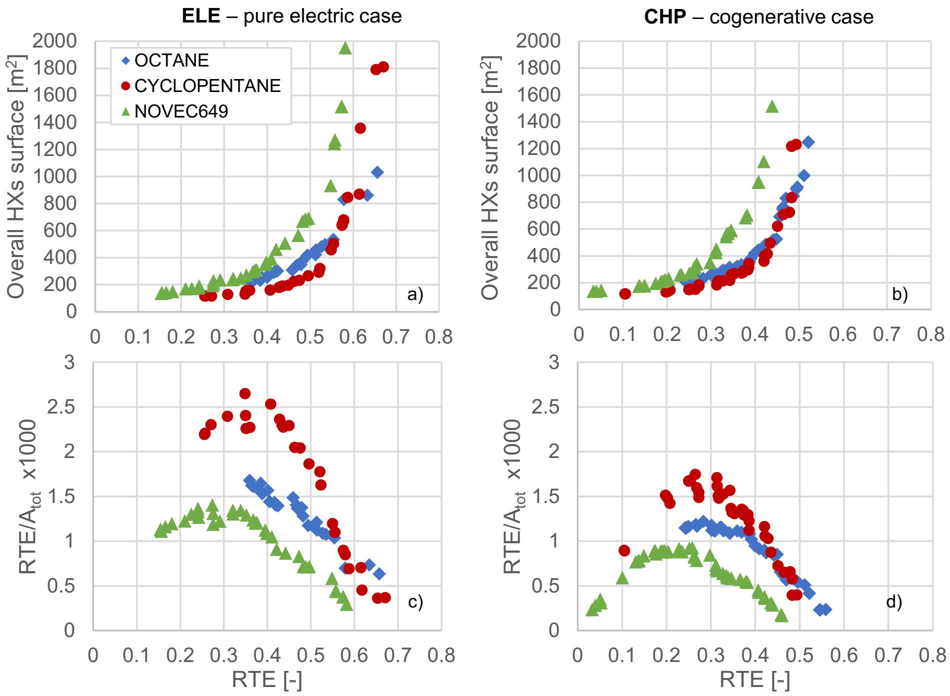

Figure 5: Comparison of the Pareto front and RTE/A_{tot} obtained with cyclopentane (red), NOVEC649 (green) and octane (blue) for both the electricity only (left) and CHP (right) cases.

5 CONCLUSIONS AND FUTURE WORKS

This work provides a numerical quantification of the performance attainable with ORC-based Carnot batteries under a realistic representation of the heat exchangers and adopting a Pareto front analysis. Two cases have been investigated with the aim of considering both pure electric (ELE) and cogenerative (CHP) applications where the ORC condensation heat is exploited by a thermal user (e.g. district heating, industrial processes like drying), as proposed by H2020 RESTORE project. Results show that cyclopentane is a promising working fluid in both cases when a waste heat integration is available in charging mode at low-mid temperature (minimum 80°C) and a reasonable temperature of the constant temperature thermal energy storage (150°C) is assumed. Round-trip efficiencies for the ELE case are around 10% higher than CHP case for the same overall heat transfer area, thanks to the lower condensation pressure and ranges between 20% for very low heat exchanger dimension up to 70% but requiring an exponential increase of the heat transfer area. Maximum RTE/A parameter, that for high heat to power ratio cycles as in this case can be considered a reasonable techno-economical figure of merit, is obtained at rather low RTE around 35% for the ELE case showing the difficulties that Carnot batteries technology may experience in getting high performance at minimum levelized cost of storage. The parameters more relevant for the analysis are the two-phase flow heat exchangers temperature differences while the pressure drops, due to the nonlinear relation with global heat transfer coefficient, have a lower impact on the overall heat transfer area and performance. Comparison of cyclopentane with respect to other fluids show that adopting a high critical temperature fluid as octane allows to potentially reach higher RTE but it also requires much larger heat transfer area because of the lower fluid density and heat transfer coefficients for average pressure drops. Differently, NOVEC649, having a lower critical temperature, can adopt smaller heat exchangers but it is penalized in cycle thermodynamic leading to a lower RTE.

Next step of this study will focus on the extension of this work towards a full techno-economic optimization where the capital cost of the system or the levelized cost of the technology will be analyzed against RTE with a Pareto front analysis.

REFERENCES

Alfani, D., Giostri, A., & Astolfi, M. (2023). Working Fluid Selection and Tthermodynamic Optimization of the Novel Renewable-Energy Based RESTORE Seasonal Storage Technology. In *Proceedings of ASME Turbo Expo 2023 Turbomachinery Technical Conference and Exposition GT2023 June 26-30, 2023, Boston, Massachusetts* (pp. 1–14).

Asgari, M., Javidan, M., Nozari, M., Asgari, A., & Ganji, D. D. (2021). Simulation of solidification process of phase change materials in a heat exchanger using branch-shaped fins. *Case Studies in Thermal Engineering*, *25*, 100835. https://doi.org/10.1016/j.csite.2020.100835

Astolfi, M., Rizzi, D., Macchi, E., & Spadacini, C. (2021). A Novel Energy Storage System Based on Carbon Dioxide Unique Thermodynamic Properties. https://doi.org/10.1115/GT2021-59487

Castell, A., Solé, C., Medrano, M., Roca, J., Cabeza, L. F., & García, D. (2008). Natural convection heat transfer coefficients in phase change material (PCM) modules with external vertical fins. *Applied Thermal Engineering*, *28*(13), 1676–1686. https://doi.org/10.1016/j.applthermaleng.2007.11.004

Cavallini, A., Col, D. Del, Doretti, L., Matkovic, M., Rossetto, L., Zilio, C., & Censi, G. (2006). Condensation in Horizontal Smooth Tubes: A New Heat Transfer Model for Heat Exchanger Design. *Heat Transfer Engineering*, *27*(8), 31–38. https://doi.org/10.1080/01457630600793970

Cheung, B., Carriveau, R., & Ting, D. S.-K. (2012). Storing Energy Underwater. *Mechanical Engineering*, *134*(12), 38–41. https://doi.org/10.1115/1.2012-DEC-3

Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, *6*(2), 182–197. https://doi.org/10.1109/4235.996017

Dumont, O., & Lemort, V. (2020). Mapping of performance of pumped thermal energy storage (Carnot battery) using waste heat recovery. *Energy*, *211*, 118963. https://doi.org/10.1016/j.energy.2020.118963

Eggers, J. R., von der Heyde, M., Thaele, S. H., Niemeyer, H., & Borowitz, T. (2022). Design and performance of a long duration electric thermal energy storage demonstration plant at megawatt-scale. *Journal of Energy Storage*, *55*, 105780. https://doi.org/10.1016/j.est.2022.105780

Eppinger, B., Zigan, L., Karl, J., & Will, S. (2020). Pumped thermal energy storage with heat pump-ORC-systems: Comparison of latent and sensible thermal storages for various fluids. *Applied Energy*, *280*, 115940.

Frate, G. F., Antonelli, M., & Desideri, U. (2017). A novel Pumped Thermal Electricity Storage (PTES) system with thermal integration. *Applied Thermal Engineering*, *121*, 1051–1058. https://doi.org/10.1016/j.applthermaleng.2017.04.127

Gnielinski, V. (1975). New equations for heat and mass transfer in the turbulent flow in pipes and channels. *NASA STI/Recon Technical Report A*, *41*(1), 8–16.

Jockenhöfer, H., Steinmann, W.-D., & Bauer, D. (2018). Detailed numerical investigation of a pumped thermal energy storage with low temperature heat integration. *Energy*, *145*, 665–676. https://doi.org/10.1016/j.energy.2017.12.087

Laughlin, R. B. (2017). Pumped thermal grid storage with heat exchange. *Journal of Renewable and Sustainable Energy*, *9*(4), 044103. https://doi.org/10.1063/1.4994054

Lemmon, E. W., Bell, I. H., Huber, M. L., & McLinden, M. O. (2018). NIST standard reference database 23: reference fluid thermodynamic and transport properties-REFPROP, Version 10.0, National Institute of Standards and Technology. *Standard Reference Data Program*.

Liu, Z., & Winterton, R. H. S. (1991). A general correlation for saturated and subcooled flow boiling in tubes and annuli, based on a nucleate pool boiling equation. *International Journal of Heat and Mass Transfer*, *34*(11), 2759–2766. https://doi.org/10.1016/0017-9310(91)90234-6

Macchi, E., & Astolfi, M. (2016). *Organic Rankine Cycle (ORC) Power Systems*. Elsevier Science.

Miller, J. (2018). *Low-cost, long-duration electrical energy storage using a CO2 -based Electro Thermal Energy Storage (ETES) system. Echogen Power Systems.*

RESTORE: Renewable Energy based seasonal Storage Technology in Order to Raise Economic and environmental sustainability of DHC. Available online at: https://www.restore-dhc.eu/. (n.d.).

Sarbu, I., & Dorca, A. (2019). Review on heat transfer analysis in thermal energy storage using latent heat storage systems and phase change materials. *International Journal of Energy Research*, *43*(1), 29–64. https://doi.org/10.1002/er.4196

Steger, D., Regensburger, C., Eppinger, B., Will, S., Karl, J., & Schlücker, E. (2020). Design aspects of a reversible heat pump-Organic rankine cycle pilot plant for energy storage. *Energy*, *208*.

Steinmann, W. D. (2014). The CHEST (Compressed Heat Energy STorage) concept for facility scale thermo mechanical energy storage. *Energy*, *69*, 543–552. https://doi.org/10.1016/j.energy.2014.03.049

Turboden S.p.A. (2023). Large-scale Heat Pumps up to 200°C to Play a Crucial Role in the Path for Decarbonization of Heating Sector. *Mitsubishi Heavy Industries Technical Review*, *60*(1), 1–5.

Williams, E. S., Panko, J., & Paustenbach, D. J. (2009). The European Union's REACH regulation: A review of its history and requirements the EU REACH regulation: A review E. S. Williams et al. *Critical Reviews in Toxicology*, *39*(7), 553–575. https://doi.org/10.1080/10408440903036056

Zhu, X., Li, Y., & Zhu, Q. (2022). Heat transfer enhancement technology for fins in phase change energy storage. *Journal of Energy Storage*, *55*, 105833. https://doi.org/10.1016/j.est.2022.105833

Žukauskas, A. (1972). Heat Transfer from Tubes in Crossflow. In *Advances in heat transfer, Academic Press* (pp. 93–160). https://doi.org/10.1016/S0065-2717(08)70038-8

223

ACKNOWLEDGEMENT

The current work has been developed for the RESTORE project (www.restore-dhc.eu/), which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101036766.

This study was carried out within the NEST - Network 4 Energy Sustainable Transition (D.D. 1243 02/08/2022, PE00000021) and received funding under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3, funded from the European Union - NextGenerationEU. This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

KCORC
KNOWLEDGE CENTER
ORGANIC RANKINE CYCLE

EDITORIAL
UNIVERSIDAD DE SEVILLA