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Lourdes García Rodríguez
(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

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PERFORMANCE AND ECONOMIC ASSESSMENT OF A THERMALLY INTEGRATED REVERSIBLE HP/ORC CARNOT BATTERY APPLIED TO DATA CENTERS

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ABSTRACT

Carnot batteries (CBs) are drawing increasing attention as grid-scale storage technologies, especially when the contribution of waste heat occurs, resulting in thermally integrated energy storages. In this context, since data centers (DCs) convert almost all the supplied electricity into recoverable waste heat, this work aims at investigating the convenience of integrating a reversible Organic Rankine Cycle (ORC)/Heat Pump (HP) Carnot battery with a DC fed by a photovoltaic power plant. For this purpose, a detailed semi-empirical off-design model of a CB is implemented in a rule-based control strategy to manage the ORC/HP operations in the integrated system. In case of renewable production surplus, the exceeding energy can be stored in the CB through the HP, which is thermally integrated with DC waste heat with the double advantage of operating with a higher coefficient of performance and of reducing the required cooling system power. The stored energy is reconverted through the ORC when the electric demand overcomes the renewable production. A sensitivity analysis varying the storage volume and the energy price has been performed to investigate the influence of such parameters on the integrated system performance. The thermal integration allows to reach roundtrip efficiencies around 37 %, although the very low operating temperatures. The CB intervention results to be economically convenient, especially when the average electricity price is high as it occurred during year 2022. The yearly additional gain, with a storage volume of 10 m^3, is assessed to be around 8270 €, and the simple payback period is less than 10 years.

1 INTRODUCTION

Today world's total electricity consumption is attributable for 2 % to data centers (DCs), due to the strong development of the Information Technology (IT) field (Huang *et al.*, 2019). Since almost the whole of DCs servers electricity demand is converted to thermal energy (Cho *et al.*, 2012), a significant amount of energy is required for cooling. For this reason, DCs are well suited for coupling with thermal energy recovery technologies, like organic Rankine cycle (ORC) power plants (Marshall and Duquette, 2022). Due to the very low temperatures at which the heat is typically released, almost all of the few works investigating this application, integrate the ORC with other technologies, especially heat pumps (HPs). Apart from Ebrahimi *et al.* (2017), who proposed the integration of an ORC system into a data center cooling system, Temiz and Dincer (2022) proposed an integrated system, which includes a parabolic trough-type concentrated solar plant with a Rankine cycle, a bifacial photovoltaic plant, a hydrogen storage system, and a Li-Br absorption refrigeration cycle. Marshall and Duquette (2022), instead, analyzed an ORC system assisted by a HP integrated in the cooling system. An alternative solution to address DCs waste heat (WH) is the residential thermal demand. Jang *et al.* (2022) proposed a waste heat recovery HP that recovers WH from a DC to satisfy the residential thermal demand. Hou *et al.* (2023) introduced a thermal energy storage (TES) for the optimal control of a DC WH consumer.

Based on the above literature review, it is interesting to investigate the integration of a Carnot battery (CB) in DC cooling systems. CBs belong to grid-scale storage technologies and represent a solution to limit the mismatch between the renewable energy source production and the electricity demand (Vecchi *et al.*, 2022). This solution has been proposed by Dumont (2017). The CB working principle is based on storing electric energy in the form of thermal energy through a heat pump, and to reconvert the stored thermal energy into electricity through a heat engine. Furthermore, CBs show higher performance when integrated in waste heat recovery systems (Frate *et al.*, 2020) (Dumont *et al.*, 2020).
In this context, this study aims at investigating the economic convenience of integrating a reversible (to reduce the investment cost) HP/ORC Carnot battery in the cooling system of a DC fed by a photovoltaic (PV) power plant. The DC waste heat is partially recovered through the HP when the PV production overcomes the DC demand, and stored at higher temperature in a sensible TES. When the PV production becomes lower than the DC electric demand, the stored thermal energy is used to power the ORC, reducing the electricity that must be purchased from the grid. Furthermore, in wintertime, the possibility of directing the high temperature thermal energy to a district heating (DH) network is included. Two different scenarios in terms of electricity and thermal energy prices are compared.

2 METHODOLOGY

In this section, the analyzed system is described and the control strategy is presented. Hypothesis, boundary conditions, and key performance indicators are defined.

2.1 The integrated system configuration

The integration of a reversible HP/ORC CB with a sensible TES in the cooling system of a DC, the main components and their function, and the energy flows are described below, according to the numbers in Figure 1:

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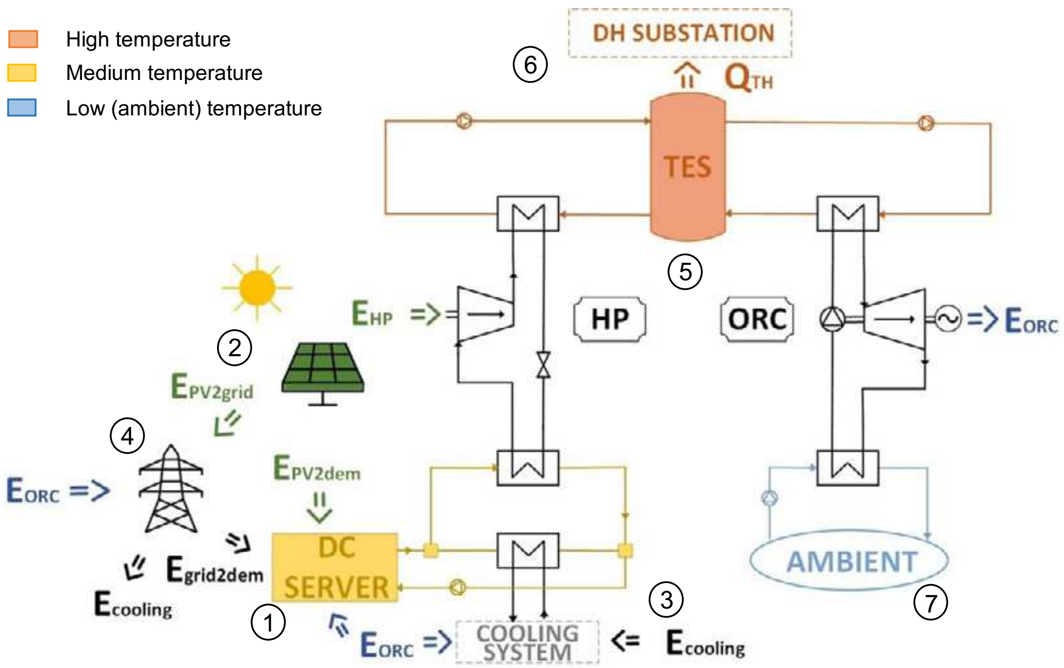

Figure 1: Integrated system configuration layout

1. An on-site DC server, which require a certain power demand, assumed constant over time.
2. An on-site solar photovoltaic power plant, which feeds the DC.
3. The DC cooling system.
4. The electric grid, which feeds the DC and the cooling system when the integrated system electricity production is not enough, and absorbs the electricity PV surplus production.

5. The reversible HP/ORC CB, which can be charged (HP mode) exploiting the PV surplus and the DC waste heat, or discharged to reconvert the heat into electricity (ORC mode) and to directly send thermal energy (thermal discharge) from the TES to a thermal user (i.e., DH).
6. A DH substation, which absorbs the thermal energy discharged by the CB.
7. The ambient, which is at the outside air temperature.

2.2 The Carnot battery model and management description

The Carnot battery scheduling management is driven by the maximization of the economic benefit provided by adding the CB to the integrated system. Indeed, the objective function (Eq. (1)) is the differential gain (ΔC) between the two configurations with and without the Carnot battery intervention.

$$\Delta C = E_{ORC} \cdot C_{el} + \Delta E_{cooling} \cdot C_{el} + Q_{TH} \cdot C_Q - E_{HP} \cdot C_{el} \quad (1)$$

The differential gain, evaluated at each time step, is equal to the sum of three positive terms minus a cost contribution. The first two positive terms are proportional to respectively the ORC energy production (E_{ORC}), and the electric energy saved from the cooling system ($\Delta E_{cooling}$) when using the HP to remove DC waste heat. These terms are multiplied by the cost of electricity (C_{el}). The third term is associated with the thermal energy sold to the thermal user (Q_{TH}), and it is proportional to the thermal energy price (C_Q). The negative contribution is related to the renewable surplus that feeds the HP (E_{HP}) in place of being sold to the grid.

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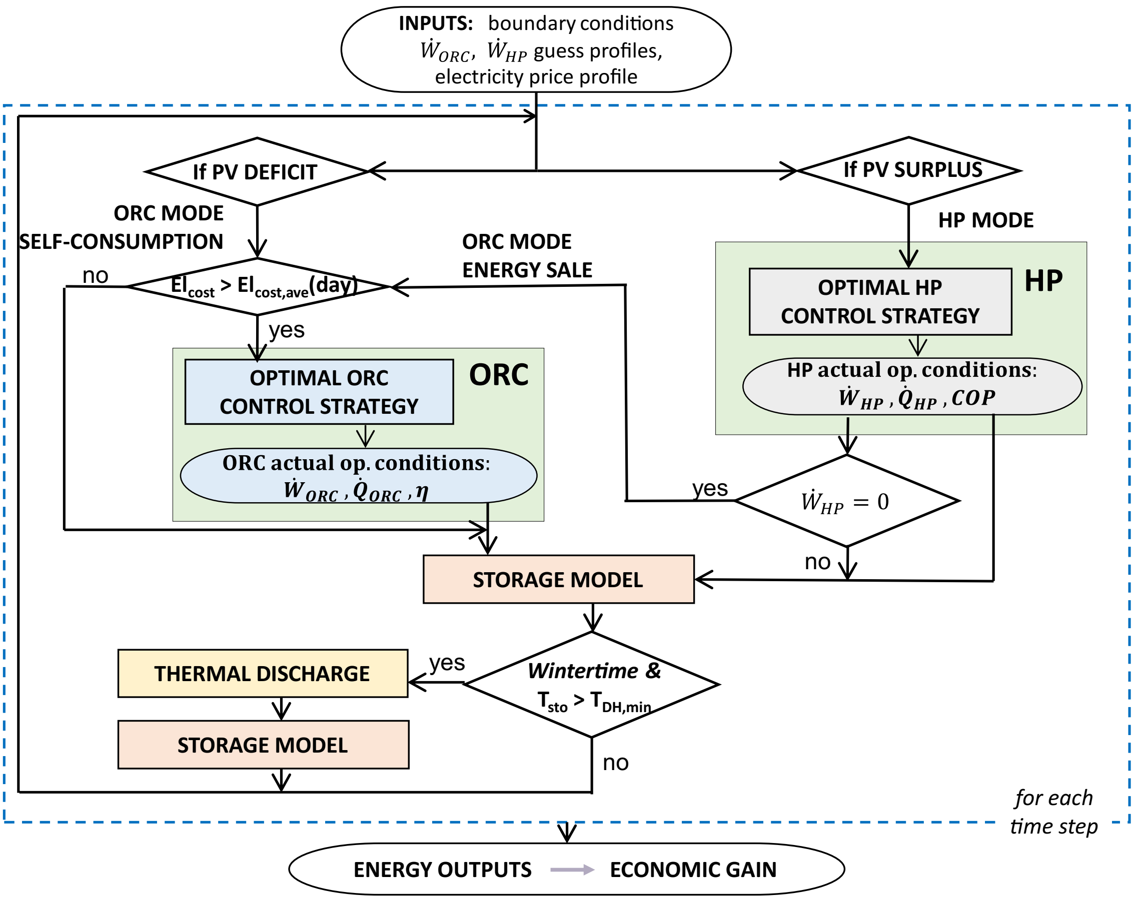

Figure 2: Carnot Battery management flowchart

The control algorithm, adopted to solve the problem, is developed according to a rule-based strategy (Figure 2). Starting from a first attempt solution, the algorithm decides to turn on/off the Carnot battery and to switch its mode (HP/ORC), according to the boundary conditions. The algorithm checks the renewable electric power availability, with reference to the DC electricity demand. In case of DC electric demand not entirely covered by the renewable production (power deficit), the algorithm checks the actual electricity price: if it is higher than the average electricity price of that day, and the available thermal power in the CB storage is enough ($T_{storage}$ > 60 °C), then the ORC is run, discharging the TES. When the renewable production overcomes the electric demand (power surplus), the HP is run absorbing the electric surplus to charge the storage ($T_{max,storage}$ = 100 °C). If the HP is not called to work, the code checks the economic convenience of running the ORC to produce a power surplus to sell to the grid. The possibility of let the HP work in power deficit, absorbing electricity from the grid when the price is low, is not consider for the sake of a conservative approach. Then, the energy balance on the TES provides the storage updated conditions in terms of temperature and availability of thermal energy. Furthermore, it is assumed that, in winter season, the eventual extra thermal energy, available in the TES at temperature higher than $T_{DH,min}$ (80 °C), can be sold to a DH substation. Thus, a thermal discharge occurs and the storage conditions are updated.

Although the algorithm checks first the possibility of discharging the ORC and then of the thermal discharge, the priority is implicitly given to the thermal discharge. More in details, in case of renewable production surplus, the HP is run to charge the storage. Then, depending on the season, two different scenarios may take place. In wintertime, as soon as the storage has reached a temperature value of $T_{DH,min}$, the HP production is sent to the thermal user. Furthermore, until there is renewable production in surplus, the HP will continue working reducing the DC cooling load. In summertime, the HP continues running until the storage is not full. Then, the storage will be discharged through the ORC as soon as it is convenient in terms of electricity price. When the storage is discharged, the HP can start again charging the storage, reducing the DC cooling load. In case of power deficit, the storage can be discharged through the ORC to produce electricity to cover the DC demand in surplus. Actually, this last situation only happens during summertime, when the storage can be left fully charged by the HP operation. Indeed, in wintertime, the HP production, as soon as it is released in the TES, it is directly sent to the thermal user, and the storage is not kept fully charged to run the ORC.

As it will be shown in the results section, it is economically convenient to address the HP thermal production to the thermal user (when possible) rather than reconvert it into electricity, to avoid the penalization due to the low electric discharging efficiency. Furthermore, it is advisable to use the HP as much as possible to reduce the cooling load associated with the cooling system (as it represents an economic revenue), and to recover the thermal energy discharged by the DC servers. 247

The routine's outputs are the HP/ORC energy values included in Eq. (1), which evaluates the economic benefit of the CB intervention.

The reversible HP/ORC system (Dumont *et al.*, 2015) has been modelled following a semi-empirical approach, rescaled and validated taking as reference the prototype installed at the Thermodynamics Laboratory of the University of Liège. For the sake of brevity, it is left to the interested reader the reference prototype experimental work (Dumont *et al.*, 2021) and the study dealing with the modelling approach (Torricelli *et al.*, 2022). The sensible TES has been modelled as a one-dimensional stratified water thermal energy storage tank.

2.3 Hypothesis, boundary conditions and performance indexes

The hypothesis and boundary conditions adopted in this study are listed in Table 1. The data center electric demand is assumed as constant and equal to 200 kW, 97 % of which is converted into heat (Wahlroos *et al.*, 2018) that needs to be removed through a cooling system composed of a chiller and fans (allowed to work only when ambient air is at temperature below 15 °C) for direct free cooling. The PV production, at each time step (15 minutes), has been calculated adopting the irradiance hourly profile in Bologna (Italy) during year 2020, as the assumed ambient temperature hourly profile (*JRC Photovoltaic Geographical Information System (PVGIS) - European Commission*, 2021). The ambient temperature influences the ORC performance and the thermal losses to the environment occurring in the TES. The storage volume has been varied from 5 to 30 m^3 with a step of 5 m^3. In addition to the cost parameters listed in Table 2, the electricity price profile derives from the hourly spot market profile in Italy in 2018 and in 2022 (*GME*, 2023). Two scenarios with very different energy prices (Figure 3) have been analyzed. The thermal energy price is constant over the year and equal to 0.08 and 0.16 €/kWh respectively in years 2018 and 2022 (*Costi e tariffe del teleriscaldamento*, 2023).

Table 1: Hypothesis and boundary conditions

Data Center	
IT + lighting and other losses electric consumption (kW)	200
Electricity converted into WH (%)	97
WH Temp. (°C)	50
Cooling System	
COP chiller (-)	4
COP fans (-) (Nadjahi *et al.*, 2018)	20
Max Temp. to use fans (°C)	15
PV Solar Panels	
Area (m^2)	2000
Efficiency (%)	25
HP/ORC Nominal Power (kW)	25
TES Volume (m^3)	from 5 to 30

Table 2: Cost parameters

Cost parameters	
HP/ORC cost (€/kW)	2500
Storage cost (€)	(Shamoushaki *et al.*, 2021)
Lifetime (years)	20
Discounted rate (%)	6
Thermal energy price (€/kWh)	0.08 / 0.16

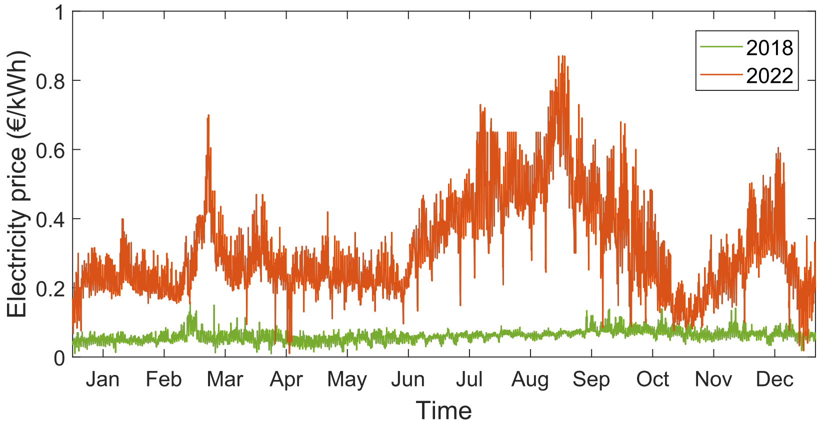

Figure 3: Yearly electricity cost profiles

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The additional revenues, due to the CB integration into the system, are associated with the ORC electrical production, the thermal production, and the energy saved from the cooling system. The expenses are due to the renewable surplus consumed by the HP (operating cost) and the levelized cost of the CB (investment cost). The payback period (PB), in the forms of simple payback period (SPB) and discounted payback period (DPB), is evaluated according to Eq. (2) and (3).

$$SPB = \frac{I_{HP/ORC} + I_{storage}}{\sum \Delta C} \tag{2}$$

$$\sum_{t=1}^{DPB} \frac{\sum \Delta C}{(1+r)^t} = I_{HP/ORC} + I_{storage} \tag{3}$$

where $I_{HP/ORC}$ and $I_{storage}$ are the investment cost of the HP/ORC and storage, r is the discount rate and ΔC is the yearly economic differential gain.
The operation of the CB is evaluated through the yearly average COP/efficiency (η_{ORC}), defined respectively for the HP mode and for the ORC mode, according to Eq. (4) and (5). The overall performance is provided by the average roundtrip efficiency, η_{rt} (Eq. (6)).

$$COP = \frac{\sum Q_{HP}}{\sum E_{HP}} \tag{4}$$

(5)

$$\eta_{ORC} = \frac{\sum E_{ORC}}{\sum Q_{ORC}}$$

$$\eta_{rt} = COP \cdot \eta_{ORC} \tag{6}$$

where Q_{HP} and Q_{ORC} are the thermal energies associated with the HP and ORC operation.
The data center and cooling system performance improvement are assessed evaluating the Power Usage Effectiveness (PUE) and the Energy Reuse Effectiveness (ERE) described respectively in Eq. (7) and (8), according to Nadjahi *et al.*, (2018).

$$PUE = \frac{E_{cooling} + E_{light\&loss} + E_{IT}}{E_{IT}} \tag{7}$$

$$ERE = \frac{E_{cooling} + E_{light\&loss} + E_{IT} - E_{reuse}}{E_{IT}} \tag{8}$$

where $E_{cooling}$ is the electricity required to cool down the servers, $E_{light\&loss}$ is the electricity lost in the energy distribution system and in other infrastructures (UPS or PDU) and to light the data center, E_{IT} is the input energy of the IT equipment, and E_{reuse} is the recovered thermal energy.
Eventually, the cooling system reduction of load, due to a partial use of the HP to cool down the data center, is described by the utilization factor (UF), which is the ratio between the cooling energy of the chiller and the fans in the two scenarios with ($E_{cooling,chiller/fans}$) and without ($E_{cooling,chiller/fans,noCB}$) the CB intervention.

$$UF_{chiller/fans} = \frac{E_{cooling,chiller/fans}}{E_{cooling,chiller/fans,noCB}} \tag{9}$$

3 RESULTS AND DISCUSSION

This section presents and discusses the techno-economic performance of the analyzed system. In the first subsection, the economic gain obtainable with the CB intervention is shown varying the storage volume, and for two different profiles of the energy price (year 2018 and year 2022). In the second subsection, the improvement of the performance due to the integration of the CB is assessed.

3.1 Carnot battery techno-economic performance

In Figure 4 and Figure 6, the additional revenues and expenses, due to the CB integration into the system, are shown with the 2018 and 2022 energy prices. The increase of the storage volume, and thus of the energy storage capacity, allows the CB to operate longer, improving the decoupling of the DC demand and the PV production. Indeed, a significant increase of the ORC production occurs. The HP electric consumption slightly increases until a certain size of the storage volume (25 m^3), and then it remains constant because it has reached its maximum production, with reference to the renewable electricity in surplus. In other words, when the storage volume is smaller than 25 m^3, it happens that, in case of renewable surplus, the HP operation can be hindered by the storage, which is already full. When the storage volume is bigger (30 m^3), the HP operation is no more prevented by the storage size, but it depends only on the availability of renewable energy in surplus (besides the hot and cold temperatures). The significant improvement of the ORC production is obtained at the expense of the thermal production, which is reduced with the increase of the storage volume. The savings from the cooling system, when using the HP to remove DC waste heat, increase with the HP production (and with the storage volume). During year 2022 the improvement in the saving is much more visible because of the significant increase in the electricity price.
The SPB and DPB values are shown in Figure 5 and Figure 7 respectively for year 2018 and 2022. When the electricity price is low (year 2018), it results that it is not convenient to add a CB to the

system, as it would require too many years to recover the investment cost (Figure 5). On the contrary, when the electricity price increases (year 2022), the integrated system with the CB becomes an interesting solution for small sizes of the storage. The payback period significantly decreases, reaching interesting values especially for relatively compact sizes of the storage volume (Figure 7).
Table 3 provides a comparison of the performance of the CB in the two reference years and for a storage volume of 10 m^3, which is the value that maximizes the economic gain (4200 € for year 2018 and 8270 € for year 2022).

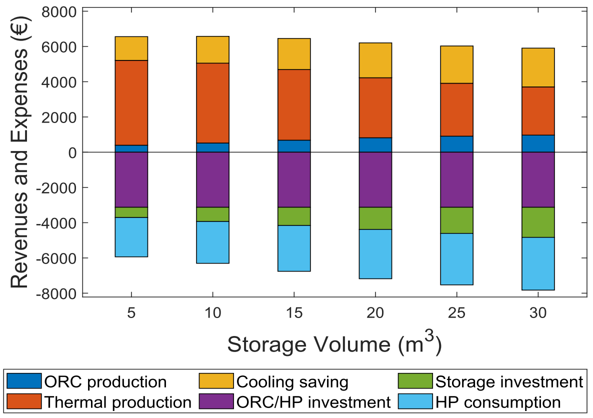

Figure 4: Economic gain due to the CB (year 2018)

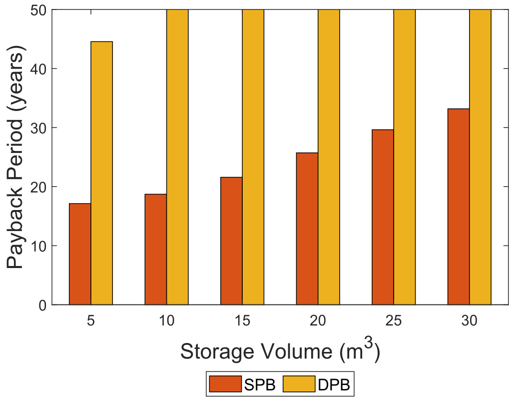

Figure 5: PB of the CB (year 2018)

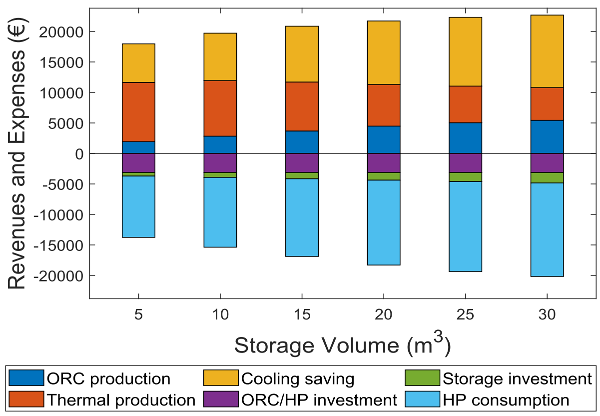

Figure 6: Economic gain due to the CB (year 2022)

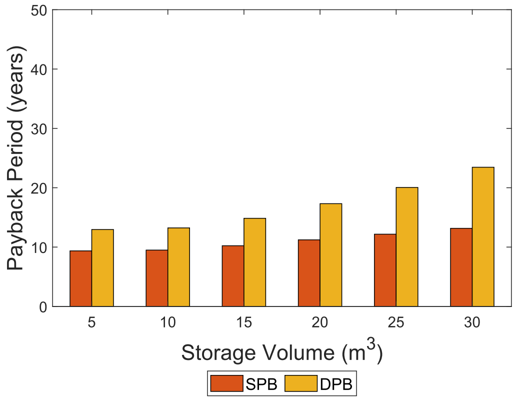

Figure 7: PB of the CB (year 2022)

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Table 3: CB performance for a storage volume of 10 m^3

	Year 2018			Year 2022			PV
	HP	ORC	TH dis.	HP	ORC	TH dis.	
Annual average COP/efficiency (-)/(%)	4.88	7.64	-	4.90	7.62	-	25
Annual electrical energy (kWh)	37649	7863	-	35689	7385	-	918994
Annual thermal energy (kWh)	183658	102882	56641	175019	96960	56972	-
Annual running hours (h)	1540	1049	467	1462	998	469	4267
Annual average roundtrip efficiency (%)	37.28		-	37.34		-	-

3.2 Integrated system overall performance

The data center PUE and ERE improve with the Carnot battery intervention (Figure 8) because part of the cooling power is provided by the HP, and about 37 % of the HP electric consumption (which is not used as thermal energy) is recovered by the ORC ($\eta_{rt} \cong 37$ %, as shown in Table 3). Since the CB intervention (running hours) increases with the storage volume, the PUE and the ERE improve with the same trend. For the same reason, a storage capacity increase allows to reduce the required cooling system power (especially of the chiller that is more energy-consuming due to the lower COP) as shown through the UF in Figure 9. To conclude, the overall performance of the integrated system seems to improve with the CB intervention, regardless of the energy price.

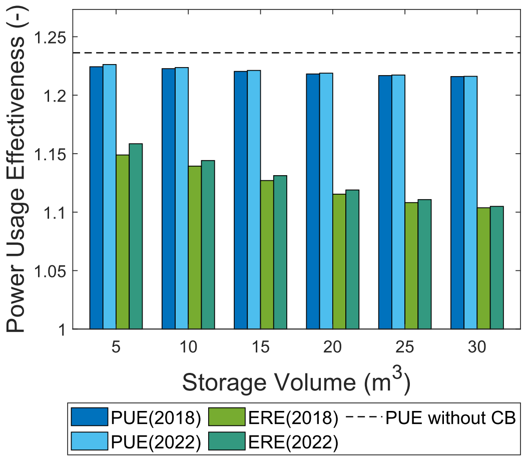

Figure 8: PUE and ERE

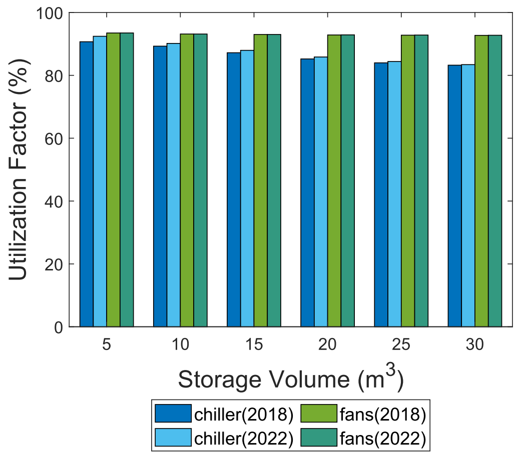

Figure 9: Utilization factor

4 CONCLUSIONS

This work enriches the current literature on the application of CB to DC waste heat recovery technologies, simulating the integration of a reversible HP/ORC Carnot battery in the cooling system of DC, which is fed by the electricity production of a PV power plant. When the PV panels produce a surplus of electricity, the exceeding energy can be stored in the CB through the HP, reducing also the cooling system load (and consumption). When the demand overcomes the renewable production, the stored thermal energy is used to power the ORC. Furthermore, during wintertime, the possibility of selling the stored thermal energy to the DH is included. With the aim to manage the ORC/HP operations in the integrated system, a rule-based control strategy is implemented. A sensitivity analysis varying the storage volume and the energy price has been performed to find out the best compromise for the storage size, and to investigate the influence of the storage capacity and the energy price on the integrated system. Results show that the Carnot battery integration is economically convenient (although the conservative hypothesis according to which the CB is not allowed to absorb electricity from the grid) especially when the energy price is high, as it occurred during year 2022. The yearly additional gain, with a storage volume of 10 m^3, is assessed to be about 8270 €, and the simple payback period is less than 10 years. Furthermore, the conservative hypothesis adopted for the CB operation, and the model validated over a prototype plant (not optimized) leave high room for improving the overall performance and the economic benefit. The thermal integration allows to reach roundtrip efficiencies around 37 %, although the very low operating temperatures. Since part of the cooling power is provided by the HP, and part of the HP electric consumption is recovered by the ORC, the data center PUE and ERE improve with the Carnot battery intervention.

Concerning the future developments, the possibility of buying electricity from the grid when the price is low, to run the HP, will be considered, and the system dynamic inertia will be included when changing the CB operating mode.

NOMENCLATURE

Δ	difference	(-)
η	efficiency	(%)
C	cost	(€)
CB	Carnot battery	
COP	coefficient of performance	(-)
DC	data center	
DPB	discounted payback period	(year)
E	electric energy	(kWh)
ERE	energy reuse effectiveness	(-)
I	investment cost	(€/kW)
PUE	power usage effectiveness	(-)
Q	thermal energy	(kWh)
r	discounted rate	(-)
SPB	simple payback period	(year)
UF	utilization factor	(%)

Subscripts

dem	demand
DH	district heating
el	electric
HP	heat pump
IT	information technology equipment
light&loss	other losses included lighting
noCB	without Carnot battery
ORC	organic Rankine cycle
PV	photovoltaic
Q	thermal energy
reuse	recovered energy
rt	roundtrip
sto/storage	thermal energy storage
TH	thermal user

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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.

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