Methodology for the sizing of a Carnot battery based on a Rankine cycle and application to a 10 kWe system for district heating application

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Abstract:
The basic technological principle of a Carnot Battery is to transform electricity into heat, store the heat and transform the heat back into electricity and/or heat. This technology has been developed more and more in the last years. This study considers the integration of a 10 kW Carnot battery in a district heating in a building with photovoltaic panels. It allows to provide both thermal and elec-trical peaks shaving. Few prototypes exist up to now and a clear methodology to size a Carnot bat-tery properly does not exist. This paper tries to draw guidelines based on a state of the art, simula-tion models and lessons learnt from experimental campaigns. The idea is to help engineers to de-veloped Carnot battery which are cheap, robust and efficient.

Keywords:
Carnot battery, electrical energy storage, district heating, heat pump, Rankine cycle, Thermal Energy Storage.

1. Introduction

1.1. Context

The share of electricity production needs to increase sharply in the next decades to decrease the impact of humans on the environment. However, there is a significant mismatch between renewable energy production and consumption. This means that electrical energy storages will play a very important role in the future. A recent alternative technology has therefore been studied for several years: the Carnot battery [1-4].

1.2. Carnot battery

The principle of a Carnot battery is rather simple: a heating cycle converts electricity into thermal energy, to store it and to use a power cycle to convert it back to electrical energy when needed. Different configurations are possible to achieve a Carnot battery (CB): the considered technology in this paper is a heat pump (HP) combined with a Rankine cycle (RC) [1-4]. This technology is interesting because it relies on massively produced components (low-cost), it allows the integration of heat flux trough the low operating temperatures and one single machine can replace the combination of the HP et RC (reversible HP/RC) [5-8].

1.3 Thermal integration

Typically, the power-to-power ratio (P2P), defined as the electrical energy output (discharge) divided by the electrical energy input (charge) is below 60% for classical CB. This is the reason why it can be helpful to valorize heat fluxes in the system to improve its performance. There are two different options to integrate heat into a CB. On the one hand, the hot storage configuration uses a heating system (heat pump in this example) to increase the waste heat temperature. This allows the power cycle (RC in this example) to increase its performance by working with a higher temperature difference. On the other hand, the cold storage configuration stores thermal energy at temperatures lower than the ambient (through a vapor cycle in this example). Once again, it allows the power cycle to work efficiently with a higher temperature difference.

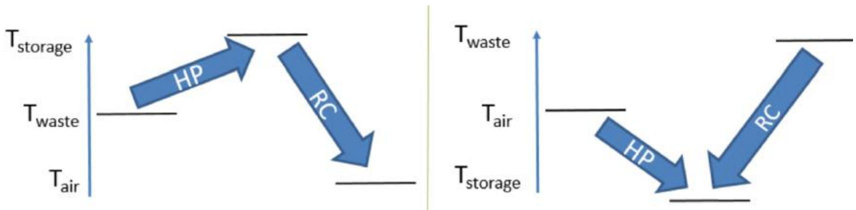

Figure. 1. Hot storage configuration versus cold storage configuration [4].

1.4 District heating

The coupling of a Carnot battery, using a hot water tank as thermal energy storage, with a district heating (DH) is promising. Figure 2 depicts an illustrative theoretical example of the system. First, it can shave the DH thermal consumption of the building (Fig. 2) through a direct use of the stored hot water. Secondly, the excess renewable production converts thermal energy from the DH in a hot water tank at higher temperature (Fig. 2). When the electrical power consumption of the building exceeds the renewable production, the CB (Rankine Cycle - RC) can convert the thermal energy into electricity to cover the electrical peak (Fig. 2).

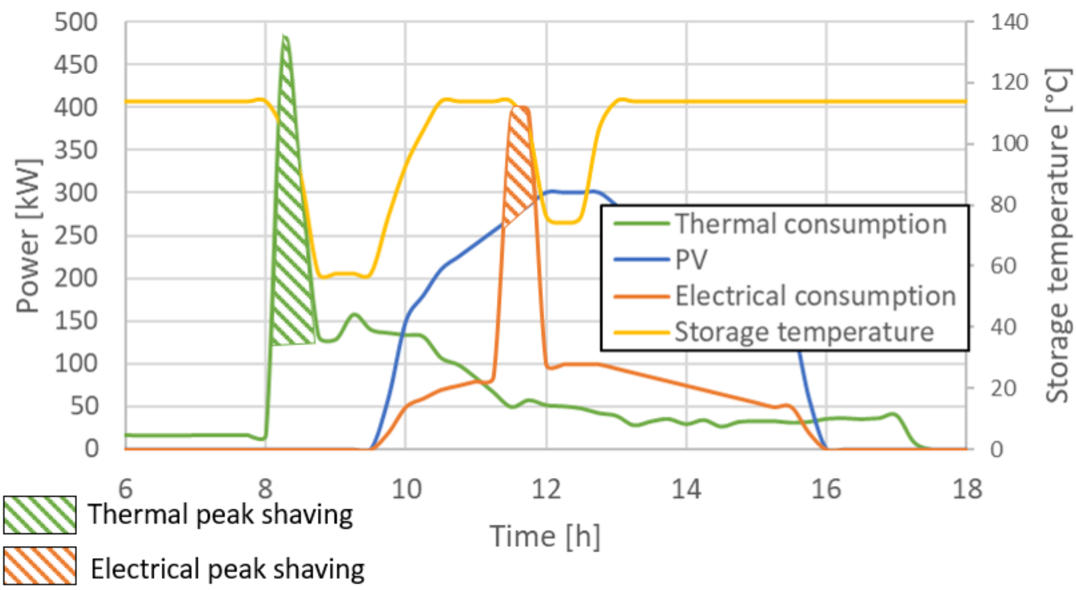

Figure. 2. Coupling of a Carnot battery using a hot water tank with a district heating

Few papers discuss the integration of such a CB with a DH. In 2019, some authors [9] show the interest of the system compared to electro-chemical batteries. To the author best knowledge, [10] is the only paper discussing the design of a CB using a reversible HP/RC system. The authors show the interest of having one single machine to decrease the investments (reversible volumetric machine and reversible heat exchangers). Sevral fluids have been considered and the optimal fluid is selected (R1233ZD) [11]. Also, the trade-off in the glide of the storage (difference between high and cold temperature) is highlighted: a high glide leads to low roundtrip efficiency while a low glide leads to a bulky hot water tank (and related high investments) [11].

1.5 Aim of the paper

This paper is only focusing on Rankine based Carnot batteries. After a short introduction, the methodology of optimal and robust sizing is exposed. The case study is described: the integration of a Carnot battery in a district heating system. Following this, the optimal design is presented. The objective is to propose a machine which is robust, optimized and cheap. Finally, a discussion analyses the results and provides guidelines for future machines.

2. Methodology

2.1. Case study

The case study is the thermodynamics laboratory of the ULiège (Belgium). Typical annual energy consumption from the DH is 344 MWh, the electrical production from PV is 568 kWh and the electrical consumption of the building is 105 MWh. The DH operates typically between 65°C and 75°C with morning peak up to 470 kW (15 mins – see Figure 2). According to Uliège data, the electrical consumption presents very high peaks (up to 200 kW) for short periods of time (few minutes), the electricity price is assumed to be 0.3 eur/kWh (buy) and 0.1 (sell) and the cost of the thermal heat from district heating is 0.07 eur/kWh.

2.2. Method

As this section will show, there is a large number of possible configurations to design a CB integrated in a given case study. For this reason, it is helpful to have guidelines to select which one should be the most profitable before performing detailed simulations. It is also possible to simulate all the configurations but this is time consuming and usually this step can be simplified thanks to some guidelines (Figure 3).

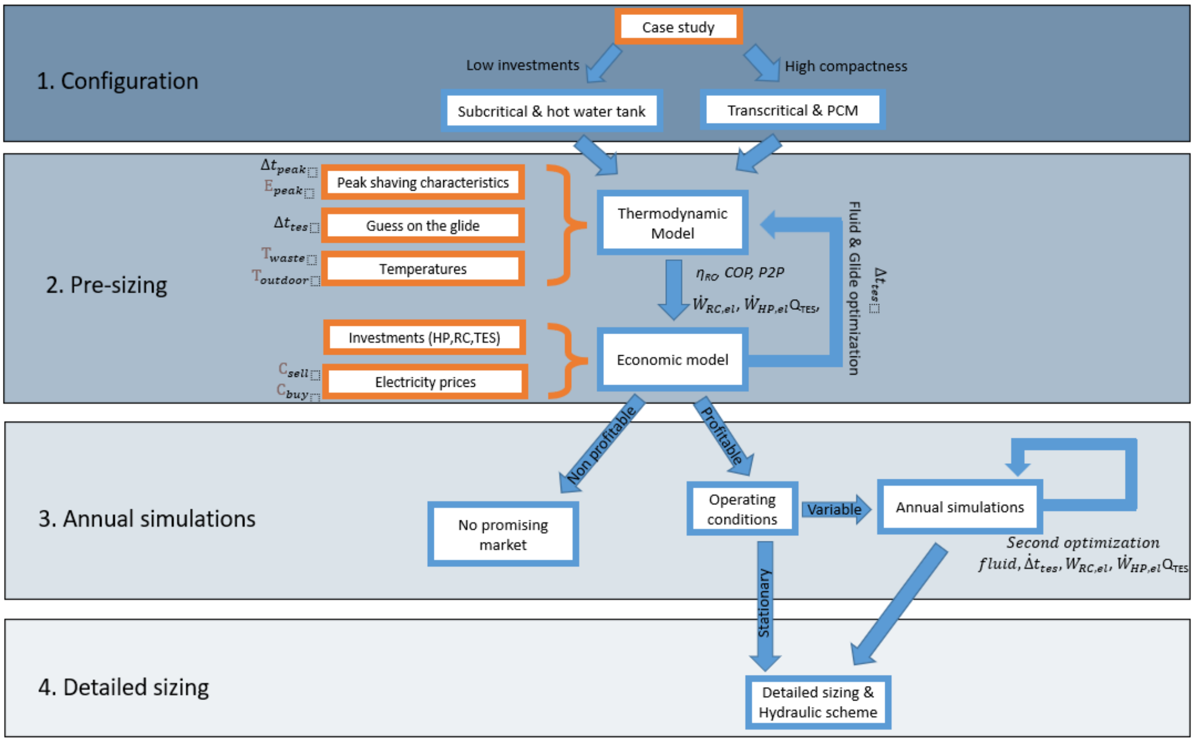

Figure. 3. Flowchart to perform the sizing of a Carnot battery based on a Rankine cycle.

2.2.1. Configuration: Selection of the configuration based on the case study

Depending on the system, constraints could be different from one application to the other.

Classically, the configuration for Rankine based Carnot battery uses a hot configuration (see section 1.3) with a subcritical thermodynamic cycle and a hot water tank. If the application presents temperature close to 0°C, then the cold configuration seems promising [10]. If no heat flux is integrated, if the heat flux allows a high temperature glide (>50 K) or if a high compactness is required, a transcritical cycle is more suitable. If an application requires a low glide, a rather low power density and a high energy density, PCM could be profitable.

Table 1. Selection of the configuration

Configuration	*Hot* Higher efficiency [11]	*Cold* Optimal for ice storage
Thermodynamic cycle	*Sub-critical* Cheap	*Transcritical* Optimal for high glides (>50 K)
Thermal energy storage	Hot water tank Low cost	PCM Optimal for low glides

2.2.2. Pre-sizing: Sizing based on the nominal conditions (temperature, power and capacity)

The main parameter to optimize is the glide of the thermal energy storage. The high thermal energy storage temperature should be optimized in order to obtain a compromise between high revenues (low glide – high power-to-power ratio) and low investments (high glide - compact storage). In the nominal point, the low temperature of the thermal energy storage should be slightly above the highest temperature of the thermal flux (waste heat or district heating) [10,11]. To start the design procedure, let's assume a guess glide (e.g. 25 K). This value will be optimized a posteriori.

Boundary conditions of the case study needs to be known (outdoor temperature, electricity price – buy (C_{buy}) and sell (C_{sell}), energy production from renewable, electrical consumption of the building and other thermal fluxes (E_{heat})). Also, the peak consumptions (thermal and/or electrical), which have to be shaved, should be identified in terms of power and duration. A decent approximation is to consider that the power of the RC ($\dot{W}_{RC,el}$) should be able to cover the difference of power between the electrical peak consumption and the base load consumption. Another approximation that can be done at this step is to consider the same power for the HP and for the RC. This allows to get comparable discharge/charge durations. Based on the nominal conditions and the a priori chosen glide, it is possible to evaluate the efficiency of the Rankine cycle and the COP of the HP. In some cases (high glides, low waste heat temperature) the COP can be very low and therefore an electrical resistance could be more profitable. Based on the RC efficiency and the COP of the HP, it is possible to identify the power-to-power ratio with a constant efficiency model [11]. An open source Matlab model using Coolprop with documentation is available [12]. The thermal energy storage should be able to store energy to cover the peak duration (Δt_{peak}). If the peak shaving is related to the thermal consumption, the capacity of the thermal energy storage (Q_{TES}) is straightforward. If the aim is to perform electrical peak shaving, the capacity of the storage can simply be computed as Eq. 1. At this step, it is important to check if the energy of the thermal flux (waste heat or district heating) is sufficient.

$$Q_{TES} = \frac{\Delta t_{peak} \dot{W}_{RC,el}}{\eta_{RC}} \qquad (1)$$

This calculation allows to compute the HP power, the RC power and the storage capacity for a given glide. The yearly benefits (Eq. 2) are expressed as the gains from electricity production of the RC (E_{RC}) and from the eventual sub-sizing of the electrical or thermal and electrical substations (*fees_{red}*) minus the cost (electricity consumed by the HP (E_{HP}) and eventual cost of the thermal flux - E_{heat}).

$$Benef_{yearly} = E_{RC} + C_{buy} - E_{HP} - C_{sell} + fees_{red}\,(\dot{W}) - (E_{heat}.C_{heat}) \quad (2)$$

The investment can be estimated through literature for the RC [13], the HP [14] and the thermal energy storage [15]. Therefore, it is possible now to simulate a wide range of glide to optimize a chosen economic indicator (Pay-Back Period, Return On Investments…). At this point, if the system does not produce benefits, the integration of a Carnot battery for the application could be of lower interest (too low-price variability, too low temperature of waste heat…). Iterations on the TES glide and the working fluid [11] are necessary to obtain the final design.

2.2.3 Annual Simulations: perform yearly simulations /off design model/control

If the working conditions of the system are similar every day of the year, this step could be skipped. If not, yearly simulations should be performed for a more detailed performance evaluation. Optimally, a dynamic model should be developed. However, since this is time consuming, a steady-state model can be used in a first approach. An optimal control strategy is mandatory in order to optimize the performance and the profitability of the system. At this step, it is possible to optimize in a more accurate way the glide, the RC and HP powers and the storage capacity.

2.2.4 Detailed sizing

Tthe power of both heat pump and RC, the glide and the capacity of the storage are defined. The selection and sizing of heat pump components are classical and manufacturers can provide accurate performance data. Generally thermostatic expansion valves are preferred because of their low cost but, in some cases, electronic expansion valves can be used (highly variable operating conditions). For the Rankine cycle, a reference book presents the process of sizing and selection for the components [17]. This paper will therefore not focus on these aspects which are already well documented. However, some specific comments can be highlighted for Carnot batteries.

If HP and RC conditions are similar, it is interesting to consider the mutualization of some components. Sometimes, only heat exchangers are shared between the HP and the RC [7,8,10] but it is also possible to use the same volumetric machine to act as a compressor and as an expander [16]. High efficiencies of the compressor and expander are crucial to obtain promising performance [6]. In this configuration it is important to control actively the circulating charge of working fluid in the system in order to obtain a high robustness and optimized performance [8]. Also, in the case of volumetric machines, the oil circulation must be ensured through a dedicated oil loop or through an optimal sizing of the piping in order to ensure sufficient speed of working fluid to entrain the oil [6]. Finally, it is possible to keep the working fluid flow direction identical in HP and RC (classical configuration) or to invert the direction of the working fluid (inverted configuration). Few comparisons exist between both systems and more information can be found in [6].

3. Results and discussion

The case study is described in section 2.1. The methodology from section 2.2 is applied to the case study to illustrate the design flowchart.

3.1. Configuration

The first step is to choose a given configuration. Because of the absence of compactness constraints, a classical sub-critical cycle with a hot water tank is chosen according to Table 1.

3.2. Pre-sizing

According to section 2.1, electrical peaks appear for a very short fraction of the time. However, thermal consumption peaks occur every morning during 15 mins. Therefore, the sizing of the machine is performed according to the thermal discharge mode. It would make less sense to size a Carnot battery to shave the electrical peak if it is only used less than 1% of the year.

From there, knowing the daily thermal consumption peak power (≈400 kW) and its duration, the capacity of the hot water tank is calculated (100 kWth). The temperature spread of the district heating is from 63°C to 77°C. Knowing this and temperature levels, the hot water tank volume can be deduced (6.1 m^3). The HP is sized in order to get a full refilling of the thermal energy storage in one hour and a half (this value comes from the PV profiles and electrical consumption of the building). Therefore, the condenser power of the HP is 80 kW. Based on the temperature levels and power aforementioned, the sizing model can be run [12]. Since the working conditions of HP and RC are similar, a reversible HP/RC system is considered. The given design values are summarized in Table 2.

Table 2. Sizing of the components

Mode	Charge - HP	Discharge - RC
Electrical power [kW]	10.7	5.6
Condenser power [kW]	82.5	94.6
Evaporator power [kW]	67.3	100
Cold temperature [°C]	62	20
Hot temperature [°C]	76	70
Scroll efficiency [%]	69.5	61.8
COP/eta [-]	7.69	5.5
Optimal volume ratio [-]	1.68	3.04
Evaporator pressure [bar]	3.34	4.05
Condenser pressure [bar]	6.02	1.18
Condenser flow (sf) [l/s]	1.4	2.6
Evaporator flow (sf) [l/s]	3.2	2.99
Working fluid mass flow rate [kg/s]	0.422	0.449
COP/eta with rv optim [-]	1%	11%

3.3. Annual simulations

Simulations of the systems have extensively been described in a former paper [18]. It confirms that the pre-sizing is economically interesting.

Results, presented in table 3, show the Carnot battery expected performance when working in each possible operating mode: the HP runs to charge the storage for about 1967 hours during a year of operation, producing about 97509 kWh of thermal energy at the expense of 19672 kWh of renewable electricity surplus, working with an average COP of almost 5; over an operating year, 65133 kWh of thermal energy is reconverted into 5331 kWh of electricity, by the Carnot battery working in RC mode for about 1296 hours, with an average efficiency of 7.92 %; eventually, for a total of 290 hours per year, the Carnot battery works in pure thermal discharge mode to cover the early morning thermal demand peaks (peak shaving), for a total amount of 18036 kWh of thermal energy.

The economic convenience of adding the Carnot battery to the integrated system is evaluated in terms of pay-back (PB) period, which is obtain dividing the Carnot battery investment cost by its annual economic benefit: the investment cost includes the HP/RC cost (a specific cost of 2000 €/kW has been considered [4]) and the TES cost [15]. The economic benefit represents the differential gain between two scenarios, namely with and without the Carnot battery intervention, that is the sum of positive and negative contributions (represented as revenues and expenses in figure 4): the positive ones are due to the DH substation downsizing (lower DH substation investment costs), the thermal demand covered by the Carnot battery instead of been provided by the DH, and the RC production both for selling and self-consumption; while the additional negative contributions include the reversible HP/RC and storage levelized investment costs, and the HP electricity consumption both from photovoltaic (PV) surplus and grid purchase. As a result, the PB period is assessed to be slightly more than 6 years, which is acceptable considering 30 years as typical lifetime period for these systems.

Table 3. Annual results

Mode	Charge - HP	Discharge - RC	Thermal discharge
Average COP/efficiency [-]	4.957	0.0792	-
Electrical energy [kWh]	19672	5331	-
Thermal energy [kWh]	97509	65133	18036
Running hours [h]	1967	1296	290
Pay-Back Period [years]		6.12	

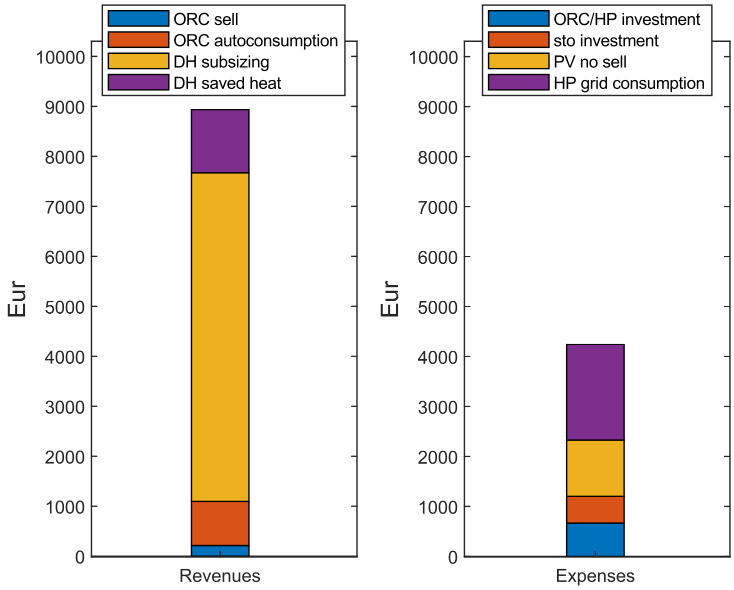

Figure. 4. Carnot Battery annual revenues and expenses

3.4. Detailed sizing in the case of the described case study

Unfortunately, it was not possible to find a suitable volumetric machine that can work properly in HP and RC mode. The proposed solution is to use three machines in parallel (table 4). Two scroll compressors ensure the compression for the HP (see Fig. 5) while three scrolls can be used for the RC (higher volumetric flow rate). The scrolls are run at constant speed. The glide of the RC is optimized to a value of 8 K for the RC. The last line of the table refers to the loss of efficiency related to the inadapted volume ratio of the volumetric machine compared to the optimal one. It would have been better to work with a machine able to vary its volume ratio actively to optimize the performance (no products were found in this operating conditions). A centrifugal pump is chosen because volumetric pumps are less robust and needs a higher degree of sub-cooling [6]. The heat exchangers are sized to reach a low pinch-point (2 K) since it significantly impacts the global performance. Also, the pressure drop on the refrigerant side is limited to 50 mbars. The expansion valve of the heat pump is electronically controlled. The liquid receiver volume is 10 liters, in order to adapt the charge depending on the operating mode.

Table 4. Description of the components

Component	Parameter	Value
Volumetric machines	Swept volume [cm3]	121
	Volume ratio	1.7
	Shaft speed [RPM]	6000
Pump	Volumetric flowrate [l/s]	0.5
	Shaft speed [RPM]	3000
LP heat exchanger	Area [m2]	15.2
	Number of plates [-]	120
HP heat exchanger	Area [m2]	17.8
	Number of plates [-]	140
Hot water tank	Volume [m3]	7
	Thermal isolation thickness (PU) [mm]	125

The layout of the system is presented in figure 5. The idea is to control the refrigerant charge through the valves. In HP mode, VLR and VEV are open while VPP is closed. In RC mode, VPP is open while VLR and VEV are closed. VEV can be opened for a short period in case there is not a sufficient charge in RC mode.

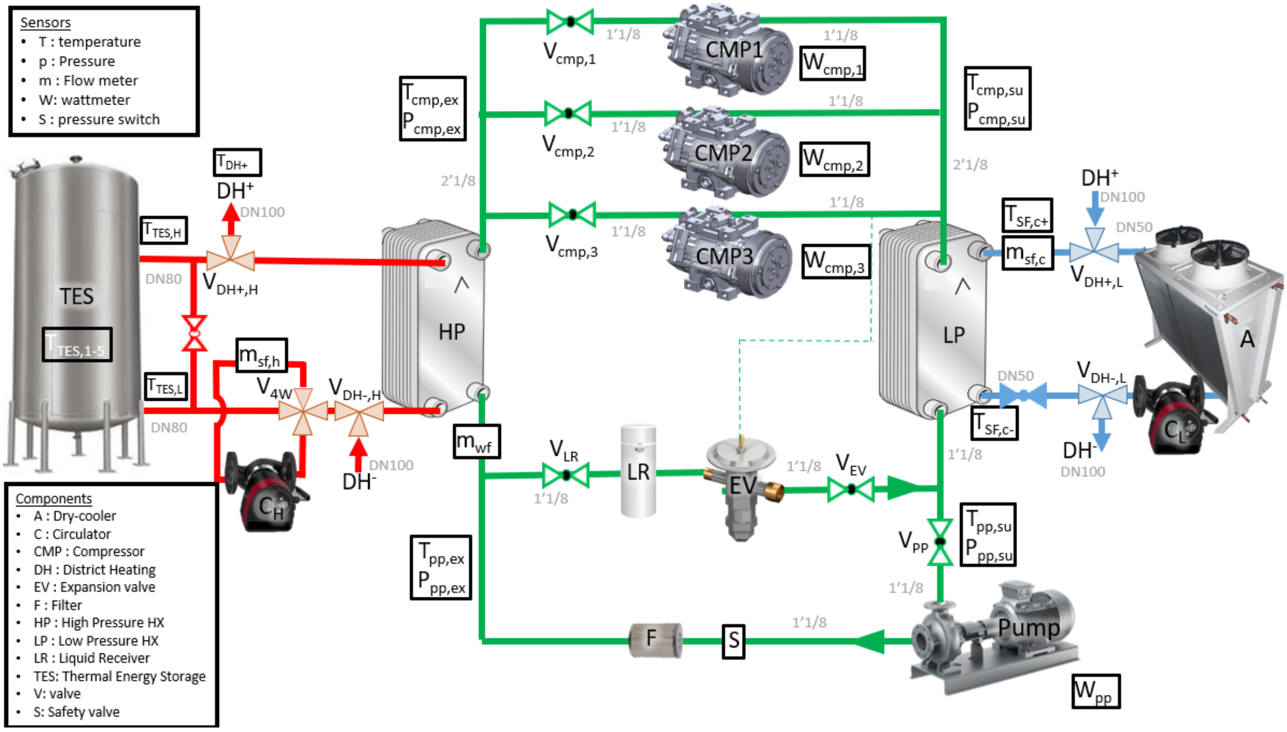

Figure. 5. Hydraulic scheme of the Carnot battery integration

In figure 5, DH- refers to the exhaust piping of the district heating (cold) while DH+ is the supply piping of the district heating (hot). In thermal discharge, the hot water circulator (CH) sends cold water from the district heating (DH-) to the hot water tank while hot water from the tank is sent to the hot part of the district heating (DH+). The other components are not used in this mode. In HP mode, the evaporator (LP heat exchanger) takes the heat from the dry-cooler or from the DH. Then, hot water is produced in the condenser (HP heat exchanger) and sent to the top of the hot water tank. In RC mode, the district heating is not used. The evaporator (HP heat exchanger) receives hot water from the top part of the thermal energy storage. The condenser dissipates its heat through the dry-cooler.

Conclusion

The design of a Carnot battery is a complex task. This paper proposes a simplified approach to choose among the possible configurations and to size the components. An illustrative case is presented with a 10 kWe machine integrated to a district heating. The next step is to test the machine and to analyze the experimental results.

Nomenclature

A	*Dry-cooler*
C	*Cost [eur]*
E	*Energy [Wh]*
M	*Flowmeter*
P	*pressure [bar]*
Q	*thermal energy [Wh]*
T	*Temperature [°C]*
t	*time [s]*
$\dot{W}$	*Power [W]*

Acronyms

CB	*Carnot Battery*
CMP	*Compressor*
DH	*District Heating*

EV *Expansion valve*

HP *Heat Pump*

PB *Pay-back*

PCM *Phase Change Material*

P2P *power to power ratio*

PV *photovoltaic panel*

RC Rankine Cycle

TES *Thermal Energy Storage*

W Powermeter

Greek symbols

η efficiency

Subscripts and superscripts

el *Electrical*

HP *High pressure*

LP *Low pressure*

red *reduction*

References

[1] Benato A, Stoppato A. Pumped Thermal Electricity Storage: A technology overview. Therm Sci Eng Prog 2018a;6:301–15. https://doi.org/10.1016/j.tsep.2018.01.017.

[2] Review of Carnot Battery Technology Commercial Development, 2022. Novotny, V., Basta, V., Smola, P., Spale, J., *Energies* **2022**, *15*(2), 647; **https://doi.org/10.3390/en15020647**

[3] Frate Guido Francesco, Antonelli M, Desideri U. A novel Pumped Thermal Electricity Storage (PTES) system with thermal integration. Appl Therm Eng 2017;121:1051–8. https://doi.org/10.1016/j.applthermaleng.2017.04.127.

[4] Dumont, O., Frate, F., Pillai, A., Lcompte, S., De Paepe, M., Lemort, V. Carnot battery technology: A state-of-the-art review. Journal of Energy Storage, 2020, 32, 101756, https://doi.org/10.1016/j.est.2020.101756

[5] Dumont, O., Quoilin, S., Lemort, V., 2015. Experimental investigation of a reversible heat pump/organic Rankine cycle unit designed to be coupled with a passive house to get a Net Zero Energy Building, International Journal of Refrigeration, 54, 190-203, https://doi.org/10.1016/j.ijrefrig.2015.03.008.

[6] Dumont, O., 2017. Investigation of a heat pump reversible into an organic Rankine cycle and its application in the building sector, PhD Dissertation.

[7] Dumont, O., Charalampidis, A., Lemort, V., 2020. First Experimental Results of a Thermally Integrated Carnot Battery Using a Reversible Heat Pump / Organic Rankine Cycle 2nd international workshop on Carnot batteries http://hdl.handle.net/2268/250924

[8] Experimental investigation of a thermally integrated carnot battery using a reversible heat pump/ organic rankine cycle: influence of system charge on performance of the reversible scroll compressor/expander and global performance, 2022. Tassenoy, R., Dumont, O., Lemort, V., De Paepe, M., Lecompte, S., International Refrigeration and Air Conditioning Conference, Proceedings.

[9] CHESTER, 2019. https://www.chester-project.eu/, consulted on the 10/10/2019.

[10] Carnot battery: Simulation and design of a reversible heat pump-organic Rankine cycle pilot plant Bernd Eppinger a,1 , Daniel Steger b,1,* , Christoph Regensburger b , Jürgen Karl c , Eberhard Schlücker b , Stefan WillApplied Energy, Volume 288, 15 April 2021, 116650

[11] Dumont., O., Lemort, V., Mapping of performance of pumped thermal energy storage (Carnot battery) using waste heat recovery, Energy 211 (2020) 118963

[12] Dumont, O., https://github.com/oliviersltsCB, consulted on the 11/10/2022.

[13] Lemmens, S., Cost Engineering Techniques and Their Applicability for Cost Estimation of Organic Rankine Cycle Systems', Energies, vol. 9, no. 7, p. 485, Jun. 2016, doi: 10.3390/en9070485.
[14] Croteau, R., Gosselin, L.,Correlations for cost of ground-source heat pumps and for the effect of temperature on their performance, International Journal of Energy Research, vol. 39, no. 3, pp. 433–438, 2015, doi: 10.1002/er.3243.
[15] Shamoushaki, M., Niknam, P.H., Talluri, L., 2021. Manfrida, G., Fiaschi, D., Development of Cost Correlations for the Economic Assessment of Power Plant Equipment, Energies, vol. 14, no. 9, p. 2665, May 2021, doi: 10.3390/en14092665.

[16] Dumont. O., Lemort., V., 2022. Pumped thermal energy storage based on ORC, Encyclopedia of energy storage, vol 2, 68-78.

[17] Macchi, E., Astolfi, M., 2017. Cover for Organic Rankine Cycle (ORC) Power Systems, Organic Rankine Cycle (ORC) Power Systems Technologies and Applications Book

[18] Torricelli, N., Branchini, L., De Pascale, A., Dumont, O., Lemort, V., 2022. OPTIMAL MANAGEMENT AND SIZING OF REVERSIBLE HEAT PUMP/ORC CARNOT BATTERIES, Turbo expo 2022.