Techno-economic assessment of a Carnot battery based on a Rankine cycle with waste heat integration

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ABSTRACT

The growth of renewable energy requires flexible, low-cost and efficient electrical storage systems to balance the mismatch between energy supply and demand. The Carnot battery (or Pumped Thermal Energy Storage) converts electric energy to thermal energy with a heat pump (HP) when electricity production is greater than demand; when electricity demand outstrips production, the Carnot battery generates power from a thermal storage (Rankine mode). Classical Carnot batteries architectures do not achieve more than 60% roundtrip electric efficiency. However, innovative architectures, using waste heat recovery (thermally integrated Carnot batteries) are able to reach electrical power production of the power cycle larger than the electrical power consumption of the heat pump (power-to-power-ratio), increasing the value of the technology. In this paper, a techno-economic comparison is proposed. An optimal system needs to take into account not only the efficiency but also the heat input availability and the working hours of a given application. Different markets and applications are considered: cogeneration, district heating, greenhouses, supermarkets and industry. The systems are compared in terms of Return On Assets. The results show that Cogeneration and district heating are the most profitable scenarii.

KEYWORDS

Carnot battery, electrical storage, heat pump, organic Rankine cycle, waste heat recovery, techno-economic.

INTRODUCTION

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. Among the available technologies, Gravity Energy Storage, Compressed Air Energy Storage and Pumped Hydro Storage are site dependent, Fuel Cells can only achieve low efficiency up to now and electrical batteries suffer from high costs and the use of rare materials [1]. A recent alternative technology has therefore been studied for several years: the Carnot battery (or Pumped Thermal Energy Storage).

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: a closed Brayton cycle [2,3], an electrical heater combined with a Rankine Cycle [4], a heat pump (HP) combined with a Rankine cycle [5,6], the Lamm-Honigmann process [7] or Liquid Air Energy Storage [8].

Reversible heat pump/organic Rankine cycle

Recently, it was proposed to decrease the costs of the Rankine cycle- based Carnot battery by having only one system acting as a heat pump or as an organic Rankine cycle (ORC) with the same components: the reversible HP/ORC system [9,10].The system is illustrated in Figure 1.

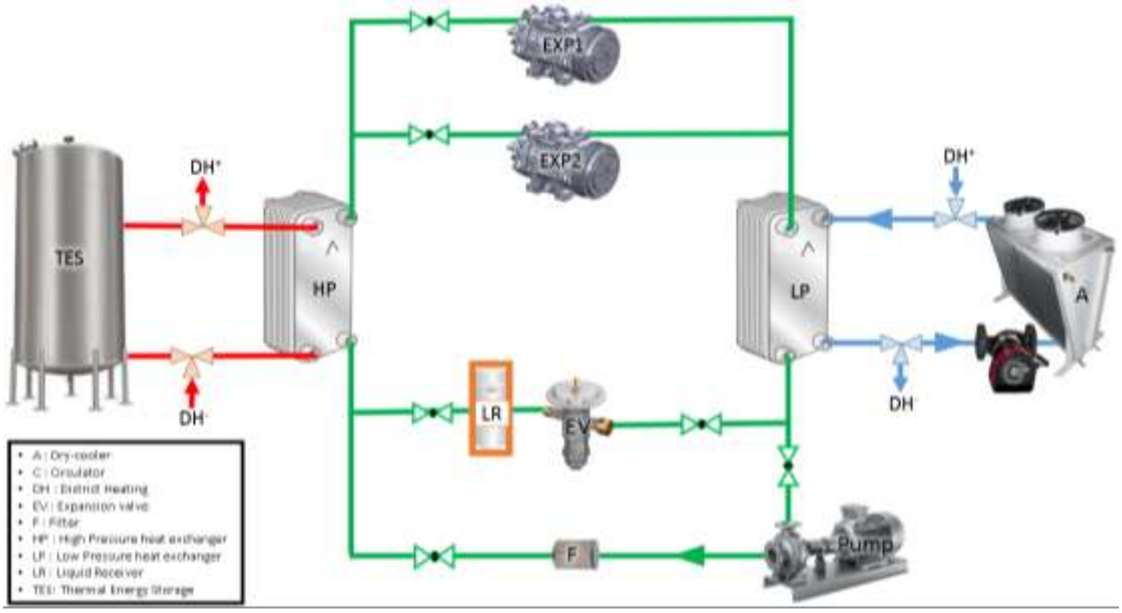

Figure 1. Reversible HP/ORC system

Thermal integration

Typically, the round-trip efficiency, defined as the electrical energy output (discharge) divided by the electrical energy input (charge), is below 70% for a standard Carnot battery. This low round-trip efficiency is the reason why it can be helpful to valorise waste heat streams in the system to improve its performance (thermally integrated Carnot battery). Some authors expect more than 100% roundtrip efficiency [11-13]. Two recent papers [12,13] showed the constraints in the sizing of a thermally integrated Carnot battery. Three constraints have to be taken into account: the energy density, the round-trip efficiency and the correct exploitation of the heat source. The main parameter to optimise is the storage temperature lift, i.e. the temperature difference between the completely charged thermal storage and the completely discharged thermal storage.

Figure 2 shows T-s diagrams for a high lift on the left (from 65°C to 85°C) and for a small lift on the right (from 75°C to 85°C) for a hot storage CB.

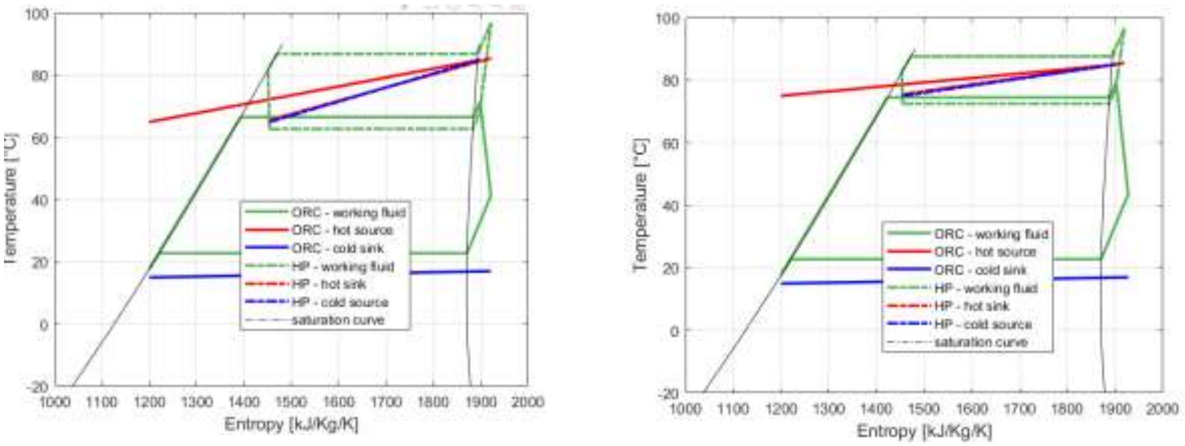

Figure 2. T-s Diagram for a high lift (left) and a low lift (right) [13].

As mentioned in recent papers [12,13], the lift needs to be optimized in the case of a thermally integrated Carnot battery. Indeed, the lower the lift, the higher the roundtrip efficiency (due to the high COP value) but the lower the compactness and the lower the waste heat energy use (this can be visualized through the difference of temperature in Figure 2). Therefore, a trade-off needs to be found depending on the case study in a way to optimize the system.

Aim of the paper

This technology is recent and the technoeconomic feasibility needs to be studied in details. The aim of this paper is to compare different case study and to identify which are the most appropriate. After the introduction, the thermodynamic model, the economic model and the case studies are presented in the methodology section. Following this, the results section presents the economic indicators of each case study and analyze them. Finally the conclusion presents perspectives of the current work.

METHODOLOGY

Thermodynamic model

A constant efficiency model is considered. The model is presented more in details in [13]. The main inputs are the waste heat and air temperatures. The pump isentropic efficiency is computed with Eq. 1.

$$\eta_{pp,is} = \frac{\dot{V}\ \ (P_{pp,ex} - P_{pp,su})}{\dot{W}_{pp,el}} \tag{1}$$

The compressor isentropic efficiency is defined by Eq. 2.

$$\eta_{cmp,is} = \frac{\dot{m}\ \ (h_{cmp,ex,is} - h_{cmp,su})}{\dot{W}_{cmp,el}} \tag{2}$$

The expander isentropic efficiency is defined by Eq. 3.

$$\eta_{exp,is} = \frac{\dot{W}_{exp,el}}{\dot{m}\ \ (h_{exp,su} - h_{exp,ex,is})} \tag{3}$$

Table 1. Inputs and parameters of the model

Parameter	Value
Evaporator pinch point [K]	2
Condenser pinch point [K]	2
Compressor isentropic efficiency [%]	75
Sub-cooling [K]	5
Superheating [K]	5
Pump isentropic efficiency [%]	50
Storage	Ideal (Plug-flow)
Pressure drop (exchangers) [bar]	0.2
Air temperature [°C]	15
Fluids	R1233zd(E)

The value of the pinch point needs to be very low. Indeed a 1K increase of this parameter leads to a roundtrip efficiency drop of 3%. This means that heat exchangers should be oversized compared to a classical application in order to reach decent efficiencies. This model is power-independent. Practically, a nominal flow of 1 kg/s is adopted for the heat pump since the flow (or power) has no influence on the observed outputs (COP (Eq. 4), RC efficiency (Eq. 5)).

$$COP \quad = \frac{Q_{cd}}{E_{el}} \tag{4}$$

$$\eta_{RC} = \frac{E_{el}}{Q_{ev}} \tag{5}$$

Two options are considered for the thermal energy storage: a hot water tank and paraffin storage (200 kJ/kg).

Economic Model

Yearly benefits are computed according to Eq. 6. They are computed as the sum of the avoided expense related to production of electricity by the ORC and the reduction of the annual fees (related to the maximum thermal and electrical peak power) minus the cost of the electricity used by the HP and the eventual expense related to the purchase of thermal energy (district heating for example).

$$Benef_{yearly} = \quad E_{ORC}\ C_{buy} \quad - \quad E_{HP}\ C_{sell} \ + \ fees\_red\,(\dot{W}) \quad - \ (E_{heat} \cdot C_{heat}) \tag{6}$$

This approach is conservative because practically sometimes local renewable electricity production cannot be sold, therefore, the cost of electricity should be zero (C_{sell}) and also because electricity prices are actual (0.15 €/kWh to buy electricity and 0.05 €/kWh for the feed-in tariff). In the future, buy prices should be higher. The cost of heat (C_{heat}) in the case of the district heating is 0.07 €/kWh. The annual fees (*fees_red*) are assumed to be equal to 631 €/kW.

The cost of the machine is very difficult to estimate properly. In the literature, a wide range of investment costs are found from 500 €/kW to 5000 €/kWh [2, 14]. The value of the most recent study [14] is taken as reference in this paper (2500 €/kW). From this paper, the storage cost can also be estimated by Eq.7.

$$C = 51+37.V -0.0003.V^2 \tag{7}$$

In the case of the PCM storage, the cost given by the manufacturer is 7 €/kg. The results are presented in term of Return On Assets (after 3 years) which is the main criteria for investor to support a new project. It is obtained by the net income divided by the total assets.

Case studies

The reversible HP/ORC system can be applied in many different applications: thermal solar panels, geothermal, incinerators, electrolyzers, industry, district heating, greenhouses, supermarkets, datacenters, residential, mobile application (trucks, boats…) and cogeneration. Not all these sectors can be studied in details. A preliminary selection is performed based on pragmatic guidelines. A reversible Carnot battery based on a reversible HP/ORC is a versatile technology but is optimally used when:

- The waste heat temperature lies above 50°C in order to obtain roundtrip efficiencies higher than 50% [13].
- The waste heat temperature is limited to 100°C in order to avoid compressor exhaust temperature above 150°C (lubrication issues).
- No constrain on volume and weight are present [13].
- The shiftable electrical power is larger than a minimum fraction of the total electrical consumption (5% in this study).

Based on this, mobile and residential application are rejected because of compactness limitations. Incinerators are not considered since the temperature levels are inappropriate. Datacenters, electrolyzers and geothermal energy are also not taken into account because of the too low shiftable electrical power. Thermal solar panels are not considered since the heat requires additional investments and is not a waste.

This selection is rather debatable and does not mean that these application should never be considered but it help focusing on the markets which are the most promising: industry, district heating, greenhouses, supermarkets, and cogeneration.

Ideally, annual simulation based on detailed dynamic models should be performed to achieve an accurate economic assessment of a given case study. However, this requires complex and CPU intensive calculations that could not be achieved for each case study. A simpler approach is proposed in order to assess and compare the economic profitability of each application. A steady-state model is used (see section Thermodynamic model) while the time the machine can be run in a year is evaluated based on the collected data (Table 2). The data is confidential and is therefore not detailed here. This data is chosen to be representative of the market but of course do not cover all the existing cases.

Table 2. Case study parameters

Application	T Waste heat [°C]	Running time [h/year]	Waste heat power [kWth]
District heating	62	182	150
Cogeneration	60	1460	70

Industry	95	292	30
Greenhouse	40	1350	70
Supermarket	40	1250	1000

The case study of the district heating is slightly different from the others since there are two options to use the thermal energy: to produce electricity with the ORC or release heat (76°C) to the district heating to fulfill peak of demand.

RESULTS AND DISCUSSION

The model presented above is used to compare case studies in terms of economic performance and compactness.

Glide optimization

Before comparing the performance, each case study is simulated with different glides (Fig. 3).

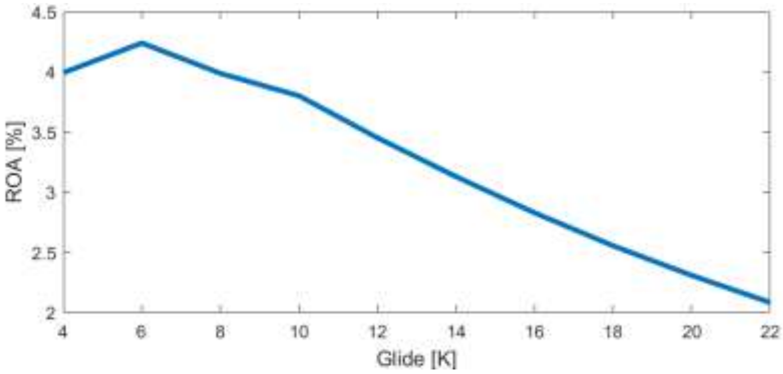

Figure 3. Glide Optimisation

The Return On Assets (ROA) shows an optimum for each case. A too low glide presents a high efficiency but high investments for the thermal energy storage (because of the low compactness. A too large glide leads to a compact thermal energy storage but to low roundtrip efficiency. So, for the sensible thermal energy storage, the glide of each case study is optimize to maximize the ROA. For the PCM storage, the glide is set constant to its minimal value to ensure phase change (7K).

Compactness

The compactness is presented for each case study the left bar correspond to the sensible storage while the right bar corresponds to the PCM storage).

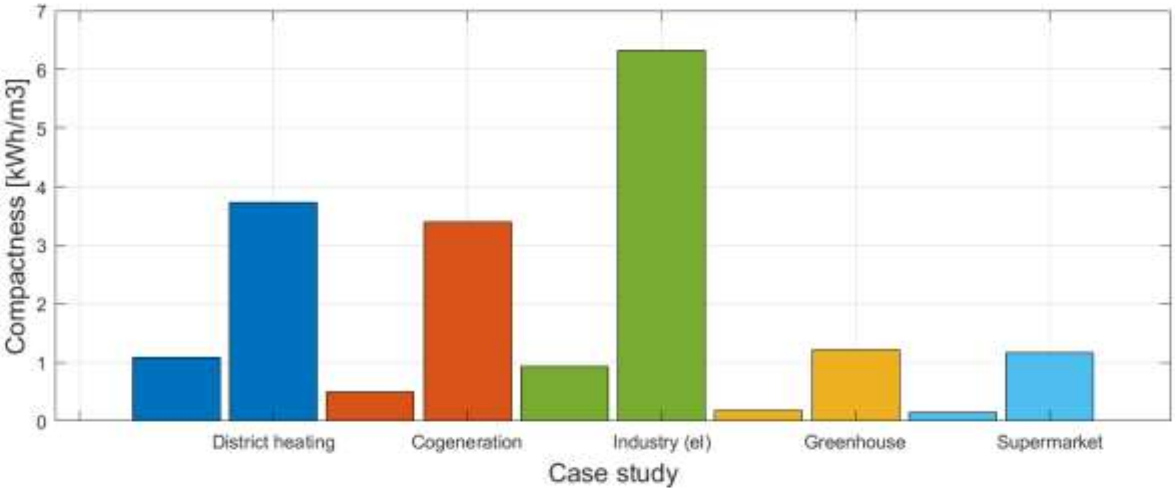

Figure 4. Compactness of the Carnot Battery (left bar = sensible storage, right bar = PCM storage).

As expected, PCM solutions present a higher compactness (factor one to six) which might be helpful in some application where compactness is important.

Return on assets

The Return On assets is evaluated for each sector (Figure 5).

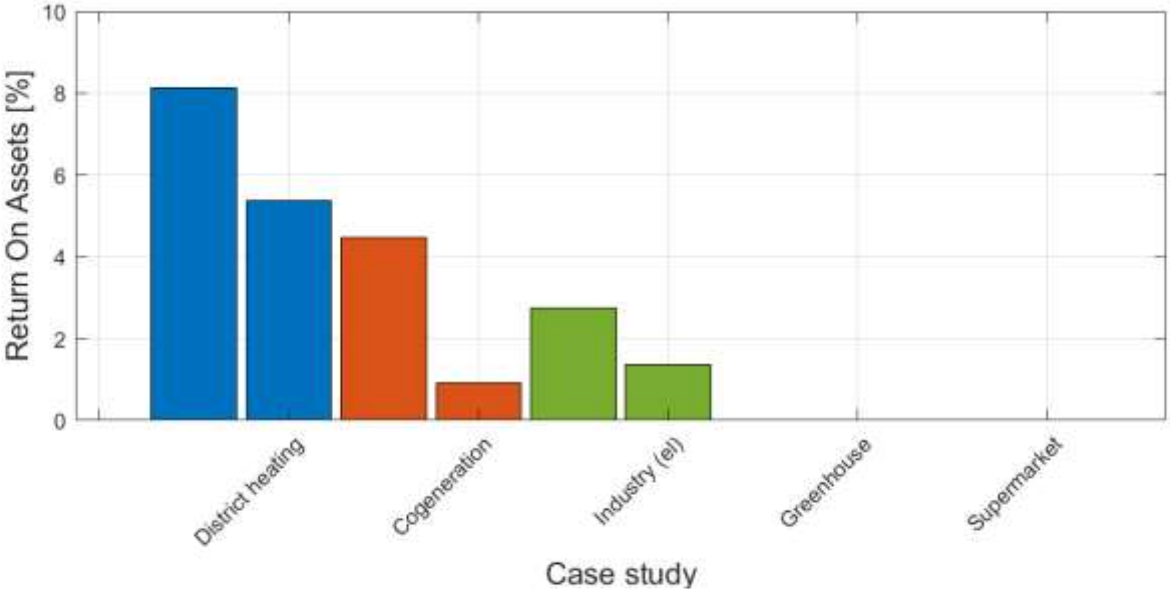

Figure 3. Return On Assets

Greenhouse and supermarket case study shows very low waste heat temperature which cannot lead to positive ROA based on the aforementioned hypothesis. It does not mean that such markets could not be favorable in some specific cases but generally, the other markets seems more promising. The industry case only presents the best third ROA, mainly because of the time of use which is limited (see Table 2). Both cogeneration and district heating system sounds very promising with high ROA dispite the conservative hypothesis. PCM solution presents a lower ROA than sensible thermal energy storages due to their high investment costs. The high ROA of District heating is mainly due to the decrease of the annual fees (Eq. 6).

CONCLUSION

Carnot battery is a burning topic due to the high importance of storing electricity. This paper investigates an economic comparison of a Carnot battery using a reversible HP/ORC system. Among all markets, the model combined with data from industry leads to promising results for both cogeneration and district heating market with Return On Assets up to 8%. This value is relatively high due to the conservative hypothesis of the model. A sensible thermal energy storage seems more interesting in terms of ROA than a latent thermal energy storage. However, PCM's lead to more compact system which might be useful for some applications.

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NOMENCLATURE

Benef	Benefits
C	Costs [€]
E	Energy [kWh]
h	Enthalpy [kJ/(Kg.K)]
$\dot{m}$	Mass flow rate [kg/s]
P	Pressure [bar]
Q	Thermal energy [kWth]
V	Olume [m3]
$\dot{V}$	Volumetric flow [m3/s]
$\dot{W}$	Power [kW]

Acronyms

CB	Carnot Battery
COP	Coefficient Of Perfomance
HP	Heat Pump
ORC	Organic Rankine Cycle
RC	Rankine Cycle

Greek

η	Efiicency [-]

Subscripts

cd	condenser
cmp	compressor
el	electrical
ex	exhaust
exp	expander
is	isentropic
pp	pump
su	supply

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