

Life cycle analysis of a Carnot battery based on a Rankine cycle (Pumped thermal energy storage)

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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 comparison with electrochemical batteries is performed. Particularly, a life cycle analysis is performed and shows the environmental benefits of the Carnot battery compared to an electrochemical battery.

Keywords:

Life cycle analysis, Carnot battery, Pumped thermal energy storage, electrochemical batteries.

1. Introduction

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).

1.1. 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].

1.2. 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].

1.3. Thermal integration

Typically, the round-trip efficiency (ϵ_{RT}), 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 6 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 TICB (example with fluid r1233ZD(E)).

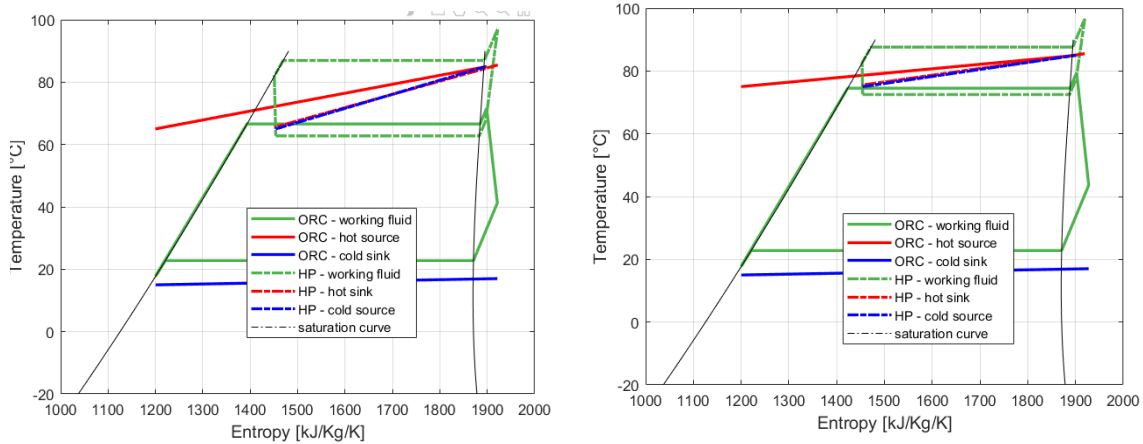


Figure 1 : T-s Diagram for a high lift (left) and a low lift (right)

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 6). Therefore, a trade-off needs to be found depending on the case study in a way to optimize the system.

1.4. Aim of the paper

The Carnot battery technology is new and very few studies are available on this promising topic. Recent papers [1-13] describe the different configurations and briefly investigate technical aspects. However the potential of this technology should be assessed in order to promote it and to have comparison with competitive technologies. This is why this paper is a first attempt to compare the impact on the environment of different Carnot batteries and to compare it with a competitive technology. After a short introduction, the methodology is exposed. The three case studies are described: two different Carnot batteries and a Li-Ion electro-chemical battery. The hypotheses to evaluate the life cycle analysis are also presented. Following this, the results are presented for the three cases according to different criteria. Finally, a discussion analyses the results.

2. Methodology

Life Cycle Assessment is a method, complying with ISO standards 14040:2006 and 14044:2006 [14,15] which assesses potential environmental impacts of a product, a process or a service through its entire life cycle. This analysis is called “cradle-to-grave” analysis and comprises all stages from raw materials extraction to end-of-life, going through materials processing, manufacture, distribution, use, repair and maintenance.

By definition, this method compiles an inventory of relevant energy and materials inputs and environmental releases of a product, through its whole life cycle. Based on this inventory, LCA assesses environmental impacts relative to these inputs and outputs and finally interprets results in relation with the defined goals.

A Life Cycle Assessment (LCA) includes four main steps:

1. Goals and scope definition
2. Inventory of relevant inputs and outputs
3. Assessment of environmental impacts related to this inventory
4. Results interpretation in relation with defined goal (analysis of the results)

3. Goal and scope definition

The aim of this study is to compare the environmental impacts of 5 electric storage systems with a power of 10 kW: Carnot battery based on a reversible heat pump/Rankine cycle with a water heat storage (10 and 25 K lifts), Carnot battery based on a reversible heat pump/RC with a phase change material heat storage (acetamide and naphthol), Li-ion battery. They are described in the inventory section.

A life cycle analysis is always a controversial task and can be achieved following different philosophies. The end of life of a given system is difficult to model. This is the reason why a cut-off method is considered in this paper. The idea is to attribute the environmental burdens of primary production to the main user of a material. If the primary material is recycled secondarily, the primary producer does not receive any credit for the supply of this recyclable material [16]. Therefore, in this analysis, only the production is considered. No maintenance or end of life elements are considered.

4. Data inventory

All the data were taken from Ecoinvent 3.6 database [17,18] based on the design of the 5 systems described below. For both the electrochemical battery and the Carnot battery, references for an electrical power of 10 kW are easily found. This is why this study focuses on this power. However, the results should not be extrapolated and other calculations should be performed for other power range.

4.1 Carnot battery based on a reversible heat pump/Rankine cycle with a water heat storage

It has been shown that Carnot batteries based on a reversible heat pump / Rankine cycle are very similar to classical heat pumps [10]. In this study, the life cycle analysis considers that the impact of the Carnot battery is equal to the impact of a classical water to water heat pump. The considered heat pump in Ecoinvent considers r134a as working fluid. The module includes the most important materials used for production. It includes also the transport of these materials, energy and water needed for production. It includes emissions of refrigerant during production and scrapping.

However, this fluid is replaced by r1234yf nowadays. The global warming potential is 335 times lower with this replacement refrigerant and therefore this is taken into account in the calculation. Also, the ODP of the working fluid r1234yf is zero. The environmental impact of the Carnot battery is the sum of the heat pump, the thermal energy storage vessel, water (as storing material) and thermal insulation. A 10kW Carnot battery (50 kWh for a 10K lift) requires a 4.2 m³ storage. The quantity of steel required is equal to 156 kg/m³ of storage and therefore 669 kg [19]. A volume of 1.4 m³ of thermal insulation is considered in this calculation with 10 cm thickness). A second case with a more compact storage is also considered. The lift is 25 K and therefore the thermal storage size is divided by 2.5 compared to the aforementioned solution.

4.2 Carnot battery based on a reversible heat pump/ORC with a phase change material heat storage

It has been shown that PCM are technically very interesting for a Carnot battery. The compactness of the system is multiplied by a factor around 4 to 5 [5]. However, it is interesting to compare other aspects like the environmental impact. The mass of steel and the thickness of the thermal insulation are proportional to the necessary volume of the storage (section 2.1.2). For the considered temperature range (around 90°C [20]), two phase change materials are found in Ecoinvent database. The acetamide and the naphthol. Those two PCM present different properties (Table 1)

Table 1. Phase change material properties

PCM	Fusion temperature [°C]	Fusion enthalpy [kJ/kg]	Density [kg/m ³]	Mass [kg]
Acetamide	80.6	36.88	57.24	2400
Naphthol	95	45.65	47.57	2836

4.3. Li-ion battery

A classical 10 kW Li-Ion battery of 88 kg is considered [6]. The lifetime is assumed to be equal to 10 years. The considered dataset includes the production of a lithium ion battery pack with 14 single cells, a steel box, a battery management system and cables are taken into account. Furthermore, the dataset includes the electric current for battery activating and testing. For infrastructure, the Ecoinvent dataset "electronic component production plant" is accounted. The single cells are assumed to be transported by ship from Beijing to Amsterdam and by lorry within Europe (1000 km).

5. Results and discussion

All the results are obtained through the Simapro software (v9.1.1.1) [15]. Several environmental impacts have been assessed using CML-IA methodology.

- Abiotic depletion refers to the depletion of non-living (abiotic) resources such as fossil fuels, minerals, clay, and peat [kg Sb eq].
- Global warming (GWP100a) refers to the impact of gas on the climatic system over a period of 100 years [Equivalent CO₂ kg]
- Ozone layer depletion (ODP) refers to the potential to destroy the ozone layer [Equivalent CFC-11 kg]
- Photochemical oxidation [kg C₂H₄ eq] refers to the reaction of sunlight with emissions from fossil fuel combustion creating other chemicals
- Acidification refers to the presence of protons in natural soils [Equivalent SO₂ kg]
- Eutrophication refers to the phosphorus present in water [Equivalent PO₄ kg]

5.1 Comparison of the five case studies

Table 2 compares the water Carnot battery with a 10 K lift (water 10 K) and with a 25 K lift (water 25K), the PCM Carnot batteries with Acetamide and Naphthol and the electrochemical battery (Li-Ion).

Table 2. LCA analysis for the five case studies (after 10 years) using CML-IA

Impact category	Water 10K	Water 25K	Acetamide	Naphthol	Li-Ion
Abiotic depletion [kg Sb eq]	0.17	0.09	0.13	0.29	0.12
Abiotic depletion (fossil fuel) [MJ]	15015	7283	36289	56647	8110
Global warming [kg CO ₂ eq]	1262	506	1791	2961	679
Ozone layer depletion [kg CFC-11 eq]	6.41E-05	2.75E-05	8.78E-05	8.4E-04	6.05E-05
Photochemical oxidation [kg C ₂ H ₄ eq]	0.64	0.37	0,62	0.99	0,52
Acidification [kg SO ₂ eq]	11.5	7.1	13.6	21.48	11.7
Eutrophication [kg PO ₄ --- eq]	4.2	2.8	3.4	1.71	5.3

From these results, it appears that PCM Carnot batteries present high impact on the environment compared to the three other cases, in all assessed categories except eutrophication and abiotic depletion. This is essentially due to the use of high quantities of phase change materials (2400 kg for the Acetamide and 2836 kg for the Naphthol). Naphthol production causes a high environmental impact because it presents the worst results in all categories except for ozone depletion layer. Among the three remaining case studies the water Carnot battery with a 10 K lift presents a much bigger impact than the 25K lift Carnot battery and the Li-Ion battery, particularly in terms of abiotic depletion, global warming and photochemical oxidation. A deeper analysis of Table 2 shows that this result comes from the large necessary tank (4.2 m³). For the two remaining technologies, it appears that the Li-Ion battery is worse according to each impact category compared to the water Carnot battery with a 25 K lift.

5.2 Carnot battery with water (25 K lift)

The Carnot battery with water (25 K lift) seems to be the best candidate to develop a renewable product able to store electricity. However, as mentioned in Table 2, the global warming potential is not negligible. Therefore, Fig. 2 compares the impact of the 4 elements constituting the Carnot battery based on this parameter.

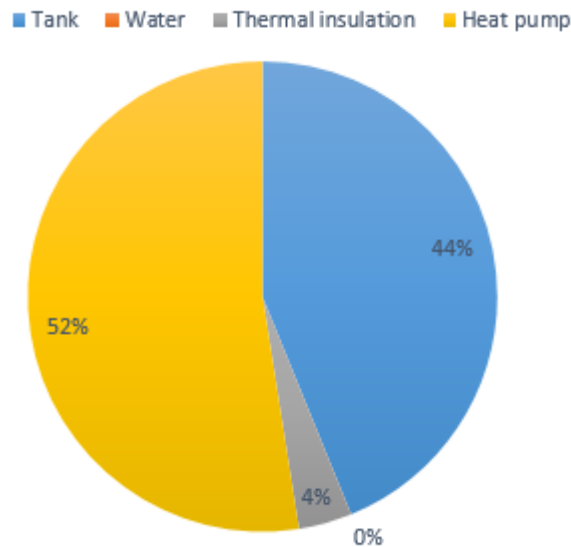


Figure 2: Carnot battery with water (25K lift)

From this, it appears that water and thermal insulation have a negligible impact. However, the heat pump and the tank are the two main contributors to the environmental impact of this solution. Improving the heat pump sustainability is possible but decreasing the tank impact seems easier. Future studies should investigate other material to store the water.

4. Conclusion

The idea of this paper is to evaluate the environmental impact of 10kW electrical storage solutions. The main conclusions are:

- Phase change materials have the strongest impact on the environment.
- The Carnot battery using water requires a significant lift (25 K) to be sufficiently compact in order to present a decent life cycle analysis.
- The water Carnot battery is better in terms of abiotic depletion, ozone depletion layer, photochemical oxidation, acidification and eutrophication but not in terms of global warming when compared with an electrochemical battery.
- It would be preferable to work on the tank of the Carnot battery to reduce its environmental impact

This study has only considered two phase change materials for the Carnot battery, one electrical power and only the production environmental cost are computed. More in depth analysis should be performed in order to obtain a better picture of the environmental impact of these technologies.

Nomenclature

HP Heat pump

LCA Life Cycle Analysis

PCM Phase Change Material

RC Rankine Cycle

s Entropy [kJ/(kg.K)]

T Temperature [°C]

Greek symbols

ε efficiency

Subscripts and superscripts

RT Roundtrip

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