Mapping of performance of pumped thermal energy storage (Carnot battery) using waste heat recovery

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ABSTRACT

The growth of renewable energy requires flexible, low-cost and efficient electrical storage to balance the mismatch between energy supply and demand. Pumped thermal energy storage (PTES) converts electric energy to thermal energy with a heat pump when electricity production is greater than demand; when electricity demand outstrips production the PTES generates power from two thermal storage reservoirs (RC mode). Classical PTES architectures do not achieve more than 60% roundtrip electric efficiency. However, innovative architectures, using waste heat recovery (thermally integrated PTES) are able to reach electrical power production of the power cycle larger than the electrical power consumption of the heat pump, increasing the value of the technology. In this paper, a general model is developed to draw mappings of performance depending on the two main inputs (waste heat and ambient air temperatures). Whatever the storage configurations, the best performances are reached when the waste heat temperature is high, the air temperature is low, and the lift of the heat pump is low. Finally, the thermally integrated PTES technology is compared with other technologies of energy storages and is theoretically promising due to its high roundtrip efficiency, its low specific price and no specific geographical conditions.

1. INTRODUCTION

1.1. Context

The share of renewable energy production is expected to grow significantly in the next decades. In this context, due to the variability of the wind and solar energy, energy storage solutions are required to provide electricity when required. In this context, the Pumped Thermal Energy Storage (PTES), or Carnot battery, is a promising technology to store electricity. Basically, a heating cycle provides heat to a hot storage by using excess electricity (charge) while a power cycle converts this stored thermal energy into electricity when required (discharge). To the author's knowledge, there is no proof of concept of this technology. However, several demonstrators are being built around the world (Malta, 2019; Chester, 2019; Isentropic, 2019). Different technologies and architectures are possible for this technology. This paper focuses on PTES using waste heat recovery (Thermally Integrated Pumped Thermal Energy Storage - TIPTES) combined with a reversible Heat Pump/Organic Rankine Cycle (HP/RC).

1.2. Thermally integrated Pumped Thermal Energy Storage

Typically, the roundtrip efficiency, defined as the electrical energy output (discharge) divided by the electrical energy input (charge) is below 70% for classical PTES. This is the reason why it can be helpful to valorize waste heat fluxes in the system to improve its roundtrip efficiency (TIPTES). Some authors expect more than 100% roundtrip efficiency (Frate et al., 2017; Peterson, 2011). The utilization of this

- higher than one - efficiency is justified by the fact that in real life the electrical input and output is generally the only indicator of performance. Compared to a classical PTES using a hot and a cold storage, there are two different options to operate a TIPTES (Fig. 1). 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 efficiency 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 vapour cycle in this example). Once again, it allows the power cycle to work efficiently with a higher temperature difference.

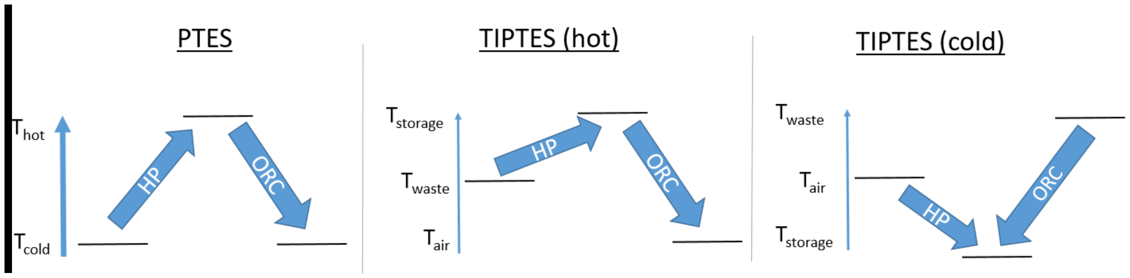

Figure 1: PTES, PTES with hot storage and PTES with cold storage

1.3. Reversible heat pump/organic Rankine cycle

The PTES unit can be a sole unit able to provide both modes with the same components (reversible HP/RC system) (Dumont, 2017; Staub et al, 2018). Indeed, heat pumps and RC power systems present many similarities for low and mid-scale systems (working fluids, volumetric machines, heat exchangers among others). The technical feasibility of such a system has been demonstrated experimentally by the authors (Dumont et al, 2015). This solution presents the advantages to be cheaper, more compact and easier to operate compared to two separate systems. In those systems, the Reynolds ratio (Eq. 1), defined as the ratio between the highest Reynolds number of the RC divided by the highest one of the HP, needs to be limited (Dumont et al, 2015). In Eq.1, the Reynolds is defined at the exhaust of the expander in RC mode and at the inlet of the compressor in HP mode. This is why areas (A) and lengths (L) are equal in both modes (see Eq. 1)

$$Re_{ratio} = \frac{Re_{RC}}{Re_{HP}} = \frac{\frac{S_{OC} L_{RC}}{\upsilon_{RC}}}{\frac{S_{HP} L_{HP}}{\upsilon_{HP}}} = \frac{\frac{\dot{m}_{RC} L_{RC}}{A_{RC} \rho_{RC} \upsilon_{RC}}}{\frac{\dot{m}_{HP} L_{HP}}{A_{HP} \rho_{HP} \upsilon_{HP}}} = \frac{\frac{\dot{m}_{RC}}{\rho_{RC} \upsilon_{RC}}}{\frac{\dot{m}_{HP}}{\rho_{HP} \upsilon_{HP}}} \qquad (1)$$

If not, the heat exchanger performance, the efficiency of the volumetric machine, the pressure drops and the oil circulation rate will be affected. The aim of this paper is to investigate the cold and hot storage configurations of thermally integrated PTES due to their high potential. In the methodology section, the modeling equations and hypotheses are presented. Following this, the results section provides mappings of performance in terms of roundtrip efficiency to understand optimal working conditions of these systems by varying the most influent parameters. Also, the energy density of such systems is assessed. In the conclusion, a comparison with competitive technologies of energy storages is analyzed

2. METHODOLOGY

The idea of this paper is to provide a general model to simulate the two aforementioned systems in a wide range of operating conditions. No detailed technological considerations are thus taken into account to obtain a general formalism. The mappings are only provided to give trends and to understand the potential of the technology. It is important to note that a more detailed model should be used in the case of the design or part load simulation of such a unit. However, it is well known that constant efficiency models are realistic in the nominal sizing conditions of the machine. This type of modeling is therefore consistent for the purpose of this paper which is to derive global mappings without entering technical details to obtain general guidelines for the technology. In this analysis, the influence of the size (power) of the system is not taken into account. Only the heat pump/ Rankine cycle combination is considered in this paper.

2.1. Heat pump and power cycle

The heat flow charts for the hot and cold storage configurations are provided in Fig. 2. Here, the considered system is a reversible heat pump/Rankine Cycle unit (HP/RC) but two separate systems for each operating mode can also be considered (Dumont, 2017). For the cold storage layout, the charging process utilizes electricity to run the compressor of the heat pump. From there, the condenser releases thermal energy in the air. Following this, the working fluid enters the expansion valve and reaches the low pressure and temperature level. The evaporator retrieves thermal energy from the cold TES. During the discharge process, the pump provides a given flow of refrigerant that is sent to the evaporator. The waste heat source evaporates the working fluid and energy is produced in the expander. In the case of the hot storage configuration, the charging process starts with the compressor of the heat pump, which increases the temperature and pressure level of the working fluid. The thermal energy is provided to the hot storage through the condenser. Then, the working fluid flows through the expansion valve to reach the low temperature and pressure side. The waste heat source is used to transform the working fluid into vapor in the evaporator. The discharge process uses the temperature difference between the hot storage and the air to run the expander and produce electricity.

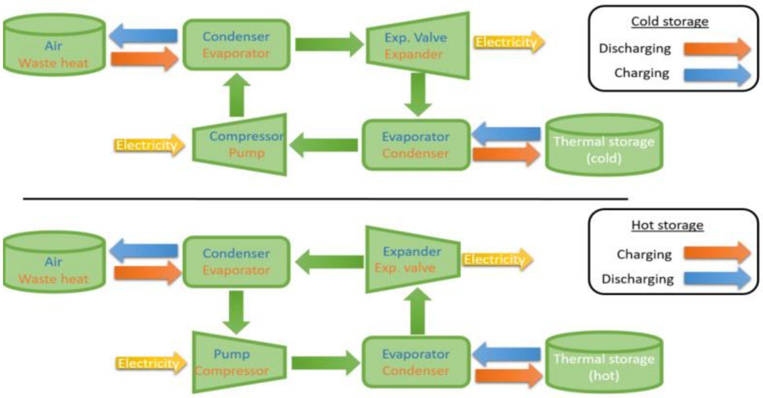

Figure 2: Heat flow chart for the hot and cold storage configurations

The modeling of the heat pump and the power cycle, assumed to be a Rankine cycle (RC) in this case, is performed based on constant efficiencies and pinch points modeling (Fig. 2). For a given configuration, the HP and the RC utilize the same working fluid for the sake of simplicity. The temperature glide corresponds to the temperature difference of the secondary fluids between the inlet and outlet of the heat exchangers but also to the temperature difference between the hot and cold parts of the thermal storages. For more clarity, T-s diagrams are shown in appendix (Fig. 1 and Fig. 2). The main inputs are the waste heat and air temperatures. Three parameters are varied to optimize the performance, namely the working fluid, the Reynolds ratio and the glide temperature.

Table 1: Value of the parameters for the constant efficiency model

	Parameter	Value
Inputs	Evaporator pinch point [K]	2
	Condenser pinch point [K]	2
	Compressor volume ratio [-]	2.2
	Maximal compressor isentropic efficiency [%]	75
	Sub-cooling [K]	5
	Superheating [K]	5
	Pump isentropic efficiency [%]	50

	Volumetric machine volume ratio	Optimal
	Storage	Ideal (Plug-flow)
	Pressure drop (exchangers) [bar]	0.2
Parameters	Evaporator/condenser glide (secondary fluid) [K]	[5-70]
	Waste heat temperature [°C]	[30-100]
	Air temperature [°C]	[0:40]
	Fluid	R1233zd(E) & R1234yf
	Reynolds ratio	[1:3]

3. RESULTS

This section aims at understanding how the inputs and parameters of the system influence the performance of the system by using the model described in the section Methodology. Performance are simulated for both working fluids R1233zd(E) and R1234yf with Coolprop. The performance is always better of R1233zd(E) and in this paper only this fluid is considered. The online appendices content the results of simulation for R1234yf (Fig. 6).

3.1. Influence of the glide

The influence of the glide temperature is depicted in Fig. 3. In this example, the roundtrip efficiency is computed with a waste heat temperature of 75°C and an air temperature of 15°C.

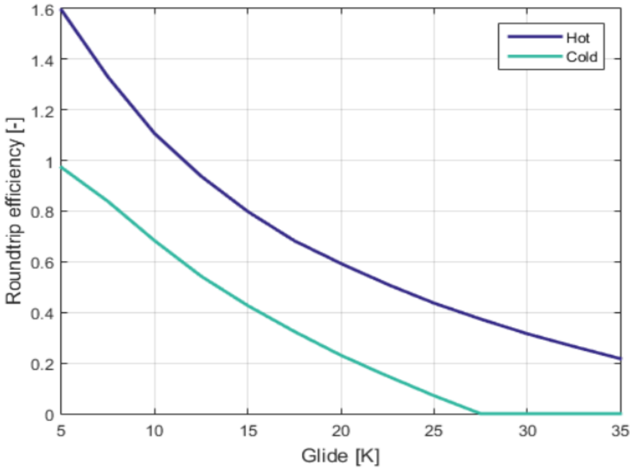

Figure 3: Influence of the glide on the roundtrip efficiency for the hot and cold storage layouts.

From Fig. 3, it appears that the hot storage configuration presents a higher roundtrip efficiency than the cold one. This observation is generalized in the next section. Also, the temperature glide needs to be limited to values below 15 K to keep a decent roundtrip efficiency. This constraint limits the compactness of sensible storage (see section compactness). In the whole paper, the glide is fixed to 10 K which is a decent compromise between performance and compactness. For the sake of completeness, mappings with 5K and 15K are also proposed in (Fig. 7 and Fig. 8).

3.2. Compactness

Before going further, it is important to quantify the energy density of such a technology. It is assumed that the volume of the heat pump and Rankine cycle are negligible compared to the size of the TES. The electrical energy for a given volume of storage can be computed through the product of the RC efficiency and the energy available in the TES for the hot storage configuration under sensible (water in this case) or latent form (200 J/g). The energy density is directly related to the Reynolds ratio. High values of Reynolds ratio (up to 3) leads to higher compactness of the system but can rise performance problems (as mentioned before). A value of one for the Reynolds ratio ensure a perfect matching of the components of the reversible HP/RC unit. As an example, the influence of the Reynolds on the compactness is plotted in Fig. 4. From this Figure, it appears that the phase change materials are promising here due to the low glide. Also, the compactness if highly affected by the working conditions, the design and the layout of the considered system. In the next part of the paper, a Reynolds ratio of one is considered to ensure an optimal performance.

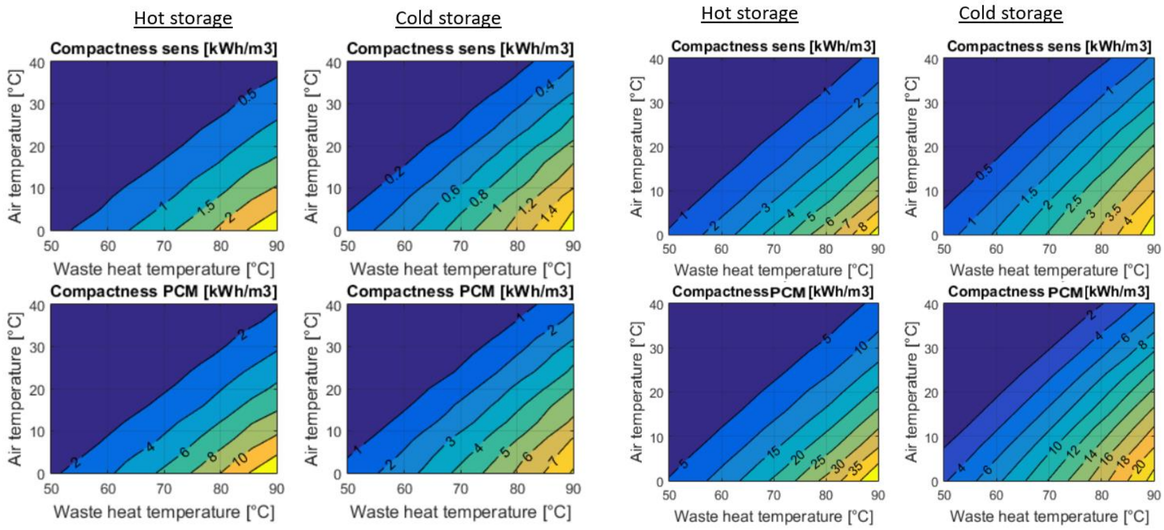

Figure 4: Compactness of the systems (left) Reynolds ratio = 1, (right) Reynolds ratio = 3.

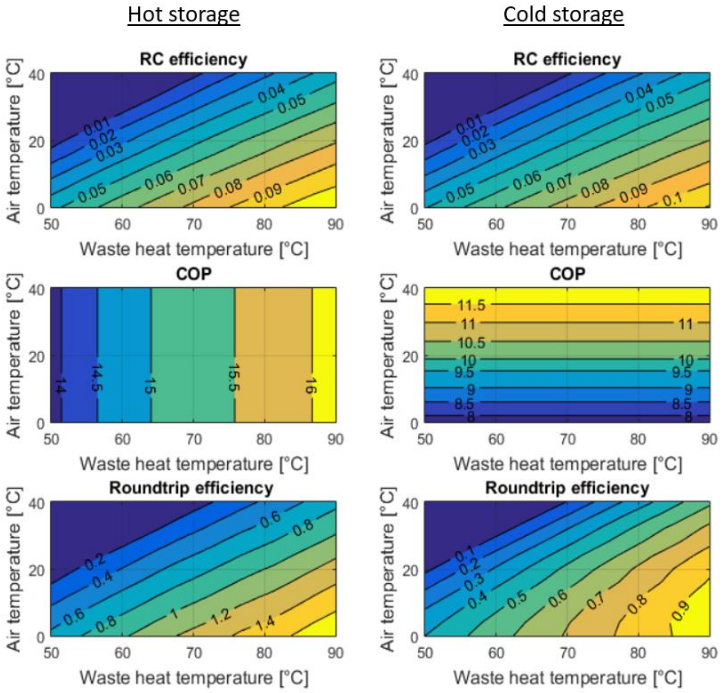

Figure 5: RC efficiency, COP of HP and roundtrip efficiency as a function of the air temperature and the waste heat temperature (glide = 10 K).

3.3. Mappings of performance

A general mapping of performance is evaluated with a glide of 10K for both hot and cold storage for a wide range of air and waste heat temperatures (Fig. 5). First, the RC efficiency naturally increases with the increase of the waste heat temperature and the decrease of the air temperature. The RC efficiency in the case of the cold storage is slightly higher due to the lower cold source temperature. The COP of the HP in the hot storage configuration is naturally independent of the air temperature and increases slightly with the waste heat temperature (see appendix). For the cold storage layout, the COP of the heat pump is obviously independent of the waste heat temperature and slightly increase with the air temperature (see appendix). Globally, the COP is rather constant due to the constant glide. This leads to a trend for the roundtrip efficiency which is similar to the RC efficiency: it increases with the waste heat temperature and decreases with the air temperature. Values with roundtrip efficiencies larger than one can be obtained for a given range of conditions. As already mentioned, the hot storage configuration outperforms the cold storage layout whatever the inputs and parameters. This is due to two facts. First, a simple analytical solution shows the highest efficiency of the hot storage layout (see appendix). Secondly, the Reynolds ratio is more severe for the cold storage layout. This means that it could be profitable to use two separate cycles (one separate HP and one separate RC) instead of a reversible system in this case.

3.4. Comparison with competitive technologies

This comparison is primarily interested in storage technologies that have a shifting capability of one day at least and the possibility to be efficient at large scale (up to MW), with characteristics such as high roundtrip efficiency, high energy density, low specific price, long lifetime. Different technologies are available in the considered range of requirements: pumped hydro-storage (PHS), fuel cells combined with hydrogen storage (FS), batteries (and flow batteries) (B), compressed air energy storage (CAES), liquid air energy storage (LAES), gravity energy storage (GES). PHS is the most widespread large-scale energy storage technology. The operating principle of PHS is to pump a fluid to a reservoir with a certain elevation when the electricity demand is low. In discharging mode, the fluid converts its potential energy in a turbine to produce electricity. CAES has also been demonstrated at large scale. In CAES, air is compressed in a given hermetic tank or underground reservoir during the charging mode and expanded in the discharge mode. However, they both require specific geological conditions [9], which significantly decreases the availability of these types of energy storages. Also, their energy density is rather low (see Table 2). Flow batteries could possibly become a useful way of storing large quantities of energy due to their large energy density (60 kWh/m^3). However they suffer from a rather low lifetime and the use of rare (or expensive) materials (Table 2).
LAES (air compression to store it in its liquid state) and GES (potential energy store by moving a large mass vertically) are not mature technologies and suffer from large energy price and low energy density. Finally, the fuel cells (hydrogen electrolyser), despite their high energy density (Table 2) present a relatively low lifetime with a limitation on the number of cycles.

Table 2: Comparison of the electrical energy storages (Diaz et al, 2016; Aneke et al., 2016 ; Gallo, A., 2016 ; Chen et al, 2009 ; White et al, 2013 ; Zakeri et al, 2015, Benato et al, 2018). *obtained with T_{air} = 20°C, T_{waste} = 75°C and ΔT = 5 K. ** located close to a waste heat source.

Technology	Energy density [kWh/m^3]	Energy price [$/kWh]	Roundtrip efficiency [%]	Lifetime [years]	Specific geographical conditions required
PHS	0.5-1.5	5-100	65-87	30-60	Yes
GES	0.5-1.5	N/A	70-86	30-40	Yes
CAES	3-12	2-200	40-95	20-60	Yes
LAES	50	260-530	40-85	20-40	No
Li-Ion B	300	500-2500	85-95	5-15	No
Flow B	16-60	120-1000	57-85	5-15	No
FS	500-3000	1-10	20-50	5-30	No
PTES	0.25-6.9	60	70-80	25-30	No
TIPTES	0.51-13.9	24*	70-200*	25-30	No**

This short summary of storage technologies with a storage period longer than a few hours shows the interest to develop and to evaluate new energy storage technologies such as the pumped thermal energy

storage (PTES). The PTES technology is interesting due to its long cycle life, no geographical limitations, no need of fossil fuel streams and capability of being integrated into conventional fossil-fuelled power plants or with any other type of waste heat source (Benato et al; 2018). As demonstrated in this paper, this type of storage is more beneficial using a waste heat source (Thermally Integrated Pumped Thermal Energy Storage) with higher roundtrip efficiencies. The values provided in (Table) are based on real data for the mature technologies (CAES, PHS, FS, B) but should be confirmed by experimental campaigns to validate them for the other types of storages.
The PTES technology should therefore be investigated with a focus on the development of a prototype demonstrating the high efficiency and the reliability of the system and on the TES storages, which need to be compact and cheap. This should help bringing the technology to the market.

4. CONCLUSION

This paper aims at evaluating the potential of the Pumped Thermal Energy Storage compared to competitive technologies. First, a review of literature shows the low roundtrip efficiency of classical PTES (<60%). However, recently a new thermally integrated PTES using a hot storage has been investigated showing high roundtrip efficiencies. This paper aims at developing mappings of performance for this system but also for an innovative concept consisting in a thermally integrated PTES using a cold storage. A constant-efficiency model is developed and leads to the following conclusions:

- The higher the glide of the heat pump, the lower the roundtrip efficiency. This means that the energy storage temperature should preferably be close to the air temperature in the case of the cold storage configuration and close to the waste heat temperature in the case of the hot storage configuration. This observation is only valid for Thermally Integrated PTES. The classical PTES roundtrip efficiency is theoretically independent of the TES temperature.
- The results show a large zone on the operating map with high roundtrip efficiencies, which makes the thermally integrated PTES technology very promising compared to other storage technologies despite the lower maturity.
- Mappings are provided to estimate which type of configuration (hot storage or cold storage) is more profitable depending on the glide, the waste heat temperature and the air temperature.

This work proves the theoretical encouraging performances of an innovative electrical energy storage. In the future, a complete economic analysis and a real proof of concept should be investigated to confirm these results.

NOMENCLATURE

A	Area	(m^2)
Air	Outdoor air	
B	Battery	
CAES	Compressed Air Energy Storage	
Cd	Condenser	
COP	Coefficient of performance	(-)
Cmp	Compressor	
Cp	Specific heat capacity	(J/(kg.K))
E	Electrical energy	(Wh)
Ev	Evaporator	
EFF	Roundtrip efficiency	(-)
Exp	Expander	
Q	Thermal energy	(Wh)
FS	Fuel cell	
g	Empirical coefficient	(-)
GES	Gravity Energy Storage	
HP	Heat Pump	
L	Typical length	(m)
LAES	Liquid Air Energy Storage	
M	Mass	(kg)
$\dot{m}$	Mass flow rate	(kg/s)
PHS	Pumped Hydro-storage	

PTES	Pumped Thermal Energy Storage	
RC	Rankine Cycle	
S	Speed	(m/s)
TIPTES	Thermally Integrated PTES	
T	Temperature	(°C)
TES	Thermal energy storage	

η	Efficiency	(-)
Δ	Difference	
υ	Kinematic viscosity	(Pa.s)
ρ	Density	(kg/s

Subscript

El	Electric
In	Inlet
Lat	Latent
Out	Outlet
Sens	Sensible
Waste	Waste heat recovery

APPENDICES

Online appendices of the paper: https://orbi.uliege.be/handle/2268/233208

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