Pumped Thermal Energy Storage Based on ORC

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Nomenclature

E Electrical energy [Wh]
Q Thermal energy [Wh]
T Temperature [K]
g g Factor [–]

Greek

ε Efficiency [–]

Subscripts

cd Condenser
ch Charging
dis Discharging
in Inlet
el Electrical
ev Evaporator
ex Exhaust
he Heat engine
hp Heat pump
rev Reversible
RT Roundtrip

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Abbreviations

CB Carnot battery
EFF Roundtrip efficiency
HP Heat pump
HT High temperature
LT Low temperature
PCM Phase change material
PTES Pumped thermal energy storage
RC Rankine cycle
TES Thermal energy storage
TI Thermally integrated

Introduction

The classical configuration of a Pumped Thermal Energy Storage (PTES) is depicted in Fig. 1. During the charging phase, a heat pump consumes electrical energy and transfers thermal energy from a Low Temperature Thermal Energy Storage (LTTES) to a High Temperature Thermal Energy Storage (HTTES). During the discharging phase, a heat engine generates electricity by converting the thermal energy stored in the HTTES and rejecting the non-converted fraction into the LTTES.

The particularity of the ORC-based PTES is to use an Organic Rankine cycle power system for the heat engine and a vapor compression refrigeration system for the heat pump. The vapor compression refrigeration cycle can be seen as the reverse Rankine cycle. It should also be mentioned that the heat pump system can be replaced by electric resistance heaters to simplify the architecture, but also increase the temperature at which thermal energy is stored.

Among the Pumped Thermal Energy Storage (PTES) technologies, two main configurations are possible: the configuration based on the Rankine cycle and the configuration based on the Brayton cycle.

Among Rankine-based PTES, the ORC-based PTES could be a valid alternative to the Brayton cycle because it generally stores energy at a much lower temperature. The advantages are:

- a better thermal integration (e.g. waste heat) thanks to the lower maximum temperature,
- easily available, cheaper and technically mature components that can be used from the HVAC industry,
- higher compactness,
- cheaper thermal energy storage due to the lower temperatures (Dumont et al., 2020a).

This chapter is organized as follows. First, the main components and subcomponents of the ORC-based PTES will be described. Secondly, possible layouts and configurations are detailed. After that, performance indicators are described. Finally, a technical state of the art including existing prototypes and key figures is given.

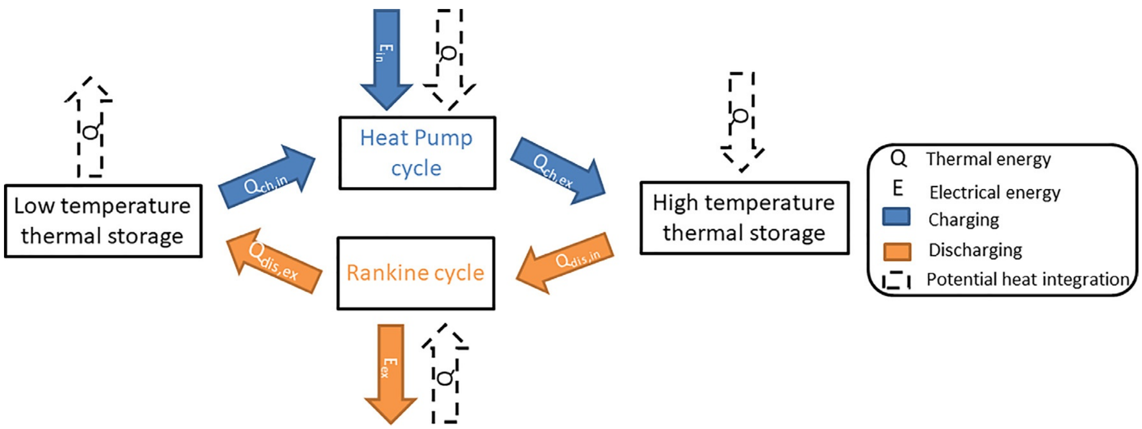

Fig. 1 Classical Rankine PTES with a heat pump and a Rankine cycle.

Components of ORC-based PTES

Vapor compression heat pump

A vapor compression heat pump transfers thermal energy from a low-temperature heat source to a high-temperature heat sink by consuming work. The four major components of a vapor compression heat pump are the compressor, the condenser, the expansion valve and the evaporator (Fig. 2A). A working fluid, named refrigerant, circulates successively through these four components in a cyclic fashion. At the supply of the compressor, the refrigerant is at a low pressure generally slightly superheated state. The vapor is compressed in the compressor, increasing its pressure and temperature. The superheated high-pressure vapor enters the condenser where it is cooled-down, condensed and generally cooled-down again so that the refrigerant at the condenser outlet is in a slightly subcooled high-pressure liquid state. The high-pressure subcooled liquid flows through the expansion valve where it is throttled down to the low pressure at the evaporator inlet. The fluid in two-phase state is routed to the evaporator where it is vaporized and slightly superheated. The thermodynamic cycle, named vapor-compression refrigeration cycle, is repeated again.

The distinction can be made between the heat pump and the refrigerator depending on the desired output of the system: the heating or the cooling effect, respectively. Vapor compression heat pumps cover a very large range of thermal power going from a few hundreds of watts to tens of megawatts. Heat pumps (refrigerators, respectively) can valorize different types of heat sources (heat sinks, respectively), such as outdoor air, ground, surface water, aquifers, solar energy directly, waste heat from engines and processes. Heat pumps (refrigerators, respectively) can heat (cool, respectively) a large variety of media, i.e., the heat sink (heat source, respectively): water, air, oil, solid materials, phase change materials (in the latter case, latent energy is harnessed in addition to sensible energy).

Advanced heat pump/refrigeration cycle architectures have been proposed in order to improve the system performance and to extend the operating conditions: recuperation with internal heat exchangers, trans-critical cycles, two-stage compression, work recovery during expansion, etc.

Organic Rankine cycle power system

A Rankine cycle power system is a heat engine converting thermal energy into work. Similar to the vapor compression heat pump, it comprises four main components: a boiler (sometimes called evaporator), a turbine, a condenser and a pump (Fig. 2B). The working fluid in a low-pressure slightly subcooled liquid state is brought to high pressure by the pump. The pump consumes power. The high-pressure liquid enters the boiler, where it is heated-up, vaporized and potentially heated again to leave the boiler in superheated vapor state. Thermal power must be supplied to the boiler by an external heat source. At the outlet of the boiler, the high-pressure vapor enters the turbine where it is expanded down to the low pressure. The turbine delivers mechanical power. As a function of the nature of the working fluid and turbine inlet state, the fluid at the end of the expansion can be in superheated vapor state or in two-phase state. At the outlet of the turbine, the fluid enters the condenser where it is condensed to liquid state and, then, slightly subcooled. Thermal power rejected at the condenser is dumped into a heat sink. The low-pressure subcooled liquid enters the pump again. The net power delivered by the Rankine cycle system is the power delivered by the turbine minus that consumed by the pump (and, potentially, auxiliaries such as the condenser fan).

The Rankine cycle power system is the technology employed in steam power plants for the electricity production. These conventional steam Rankine cycle power systems use water as the working fluid. Other working fluids than water can be used. The term Organic Rankine Cycle (ORC) is used when the working fluid contains carbon, but the definition is generally extended to include ammonia.

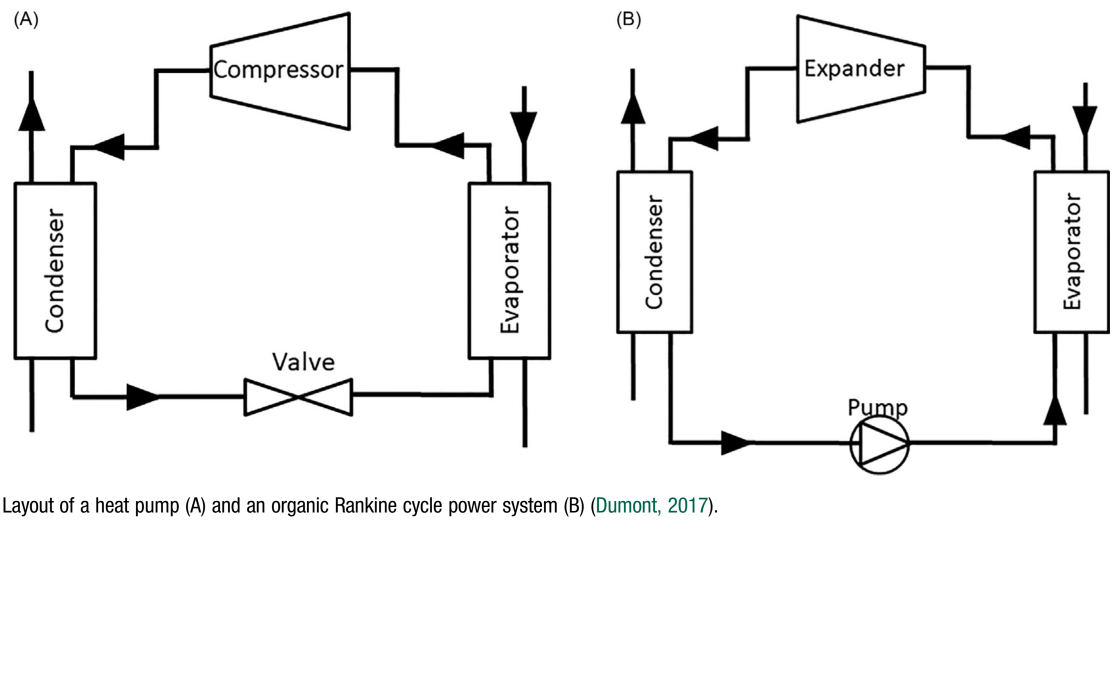

Fig. 2 Layout of a heat pump (A) and an organic Rankine cycle power system (B) (Dumont, 2017).

Similar to heat pump cycles, the Organic Rankine cycle could be modified in order to improve its performance. During the last decades (Dumont et al., 2018; Macchi and Astolfi, 2016; Lecompte et al., 2015), intense research has also been conducted on ORC to propose advanced architectures leading to a best match with heat source and heat sink temperature profiles (by decreasing external irreversibilities): transcritical cycles, flash, triangular (or trilateral) cycles, multiple evaporating pressures, use of zeotropic mixtures of fluids, etc. Also, the use of a recuperator inside the cycle, in the case of dry working fluids, allows for recovering the sensible heat at the turbine outlet to preheat the liquid at the pump outlet. This yields a higher cycle efficiency, decreases the thermal load at the condenser and can be a way to limit the temperature decrease of the heat source (for instance, to prevent any formation of corrosive condensates in fumes).

Working fluids

In both the vapor compression heat pump and the ORC power system, a working fluid flows successively through the different components of the system and describes a thermodynamic cycle. The working fluid can be natural fluid (NH_3, CO_2, hydrocarbons) or synthetic fluid (HFC, HFO, etc.). Zeotropic mixtures of fluids can also be considered. In both the heat pump and the ORC, the choice of working fluid results from a trade-off between many criteria including energy performance, size of components, cost of fluid and components, environmental impact and security. The selection of the working fluid has been at the center of intense research the last decades and is continuously evolving due to the development of new fluids and to the implementation of new regulations (Macchi and Astolfi, 2016).

Thermal energy storage (TES)

In a Rankine PTES based on ORC systems, temperature levels are usually low. Therefore, water is generally used as the storage medium due to its low cost and simplicity of use (for temperature lower than 150 °C). Mineral oil could be used for higher temperatures up to about 300 °C at ambient pressure. PCM are also considered due to their high compactness, but their costs have been limiting their use up to now. It is also possible to have a hybrid configuration with a sensible and a latent TES in order to obtain a perfect match of the temperature profiles (Dumont et al., 2020a). Also, sometimes only one thermal energy storage is used. In this case, one of the storage units is replaced by the ambient air (Dumont et al., 2020a).

Configurations of ORC-based PTES

Basic configuration

The basic configuration of the ORC-based PTES is depicted in Fig. 1. In this configuration, described in the introduction, thermal energy integration (through the use of waste heat for example) is not considered.

A general simple analytical model can be expressed based on the Carnot efficiency assuming a perfectly stratified storage with no losses (the thermal energy storage contains two separated zones (one at the high temperature (T_{hot}) and one at the low temperature (T_{low}))). The heat pump coefficient of performance (COP) is defined by Eq. (1) (Dumont, 2017). It corresponds to the COP of a Carnot system multiplied by a factor (g) taking into account all the irreversibilities and physical constraints.

$$COP_{HP} = \frac{Q_{cd}}{E_{el}} = g_{HP}\frac{T_{hot}}{T_{hot} - \mathrm{T}_{cold}} \tag{1}$$

The Rankine cycle (RC) efficiency is defined by the Carnot efficiency multiplied by a factor (g) taking into account all the irreversibilities and physical constraints (Eq. 2; Dumont, 2017).

$$\eta_{RC} = \frac{E_{el}}{Q_{ev}} = g_{RC}\left(1 - \frac{T_{cold}}{T_{hot}}\right) \tag{2}$$

The roundtrip efficiency (EFF) is defined as the ratio of the electrical output of the ORC power system to the electrical input of the heat pump. Since the thermal energy at the condenser of the heat pump and that at the evaporator of the ORC are equal, the roundtrip efficiency is defined by the product of Eqs. (1) and (2), which leads to Eq. (3) for the hot storage configuration (see section "Thermally integrated pumped thermal energy storage (TIPTES)"). In that configuration, the roundtrip efficiency (EFF) is simply the product of g_{HP} and g_{RC} of the heat pump and of the Rankine cycle.

$$EFF_{roundtrip} = COP_{HP} \cdot \eta_{RC} = g_{HP}\frac{T_{hot}}{T_{hot} - T_{cold}} g_{RC}\left(1 - \frac{T_{cold}}{T_{hot}}\right) = g_{HP} \cdot g_{RC} \tag{3}$$

These "g factors", which are the second law efficiencies of both machines, are representative of the perfection of the thermodynamic cycles. A simple and low-cost system usually presents a g factor lower limit around 0.4 while large scale, advanced architectures with more investments lead to high values of g factor. Therefore, in a way to encompass all the possibilities, Fig. 3 depicts the roundtrip efficiency as a function of the g factors of the heat pump and of the Rankine cycle.

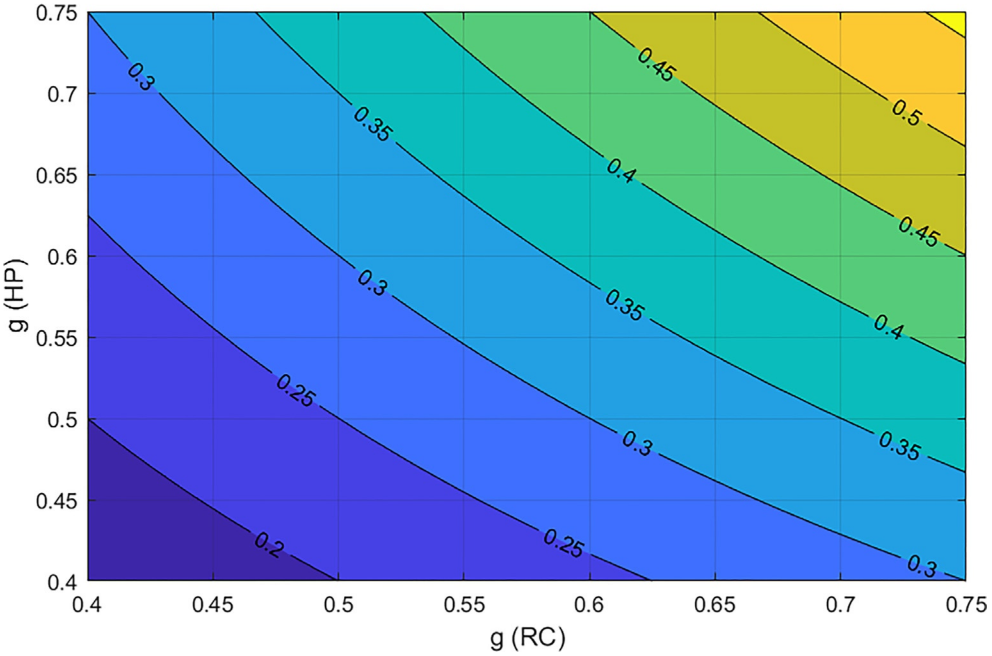

Fig. 3 Roundtrip efficiency as a function of second-law efficiencies of the heat pump (HP) and Rankine cycle (RC).

The roundtrip efficiency (*EFF*) never reaches values above 50%. This is not an issue since this technology is highly recyclable, scalable and site-independent unlike other electrical storage solutions (Dumont, 2017).

Thermally integrated pumped thermal energy storage (TIPTES)

The low round-trip efficiency achieved with the basic configuration of a PTES is the reason why it can be helpful to valorize waste heat streams in the system to improve its performance (thermally integrated PTES - TIPTES). Waste thermal energy can be used to increase the thermal content of the HTTES (Fig. 1), increase the evaporating temperature in the HP or be directly converted by the RC (Fig. 1). Also, the heat released by the ORC condenser (or by the HP condenser in the case of the cold storage configuration described later) could be valorized for low temperature heating purposes. Some authors expect more than 100% roundtrip efficiency (Francesco et al., 2017; Dumont and Lemort, 2020). When using a thermally integrated Carnot battery, two different options are possible for the thermal energy storage: the hot and the cold layout configurations (Fig. 4).

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 Rankine cycle 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 vapor compression cycle in this example). Only a few references discuss this possibility (Dumont and Lemort, 2020; AES, 2019). Once again, it allows the power cycle to work efficiently with a higher temperature difference. From a thermodynamic point of view, it can be shown (analytically or with a constant efficiency model) that the round-trip efficiency is always higher for the hot storage configuration (Dumont and Lemort, 2020). This does not mean that the cold storage layout cannot present other advantages (a more straightforward use of latent energy storage, ice, for example).

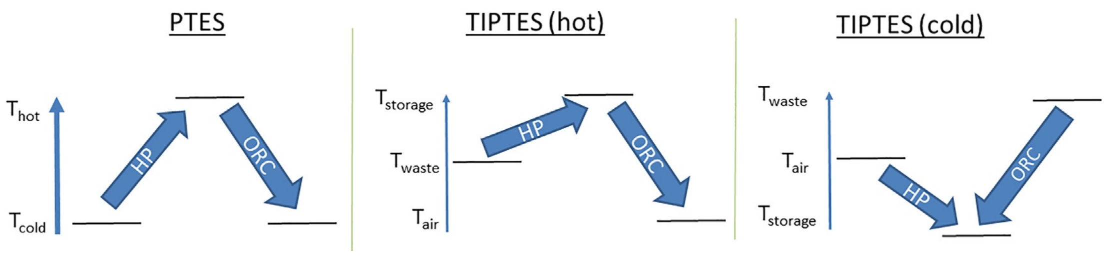

Fig. 4 High Temperature layout versus cold temperature layout (Dumont and Lemort, 2020).

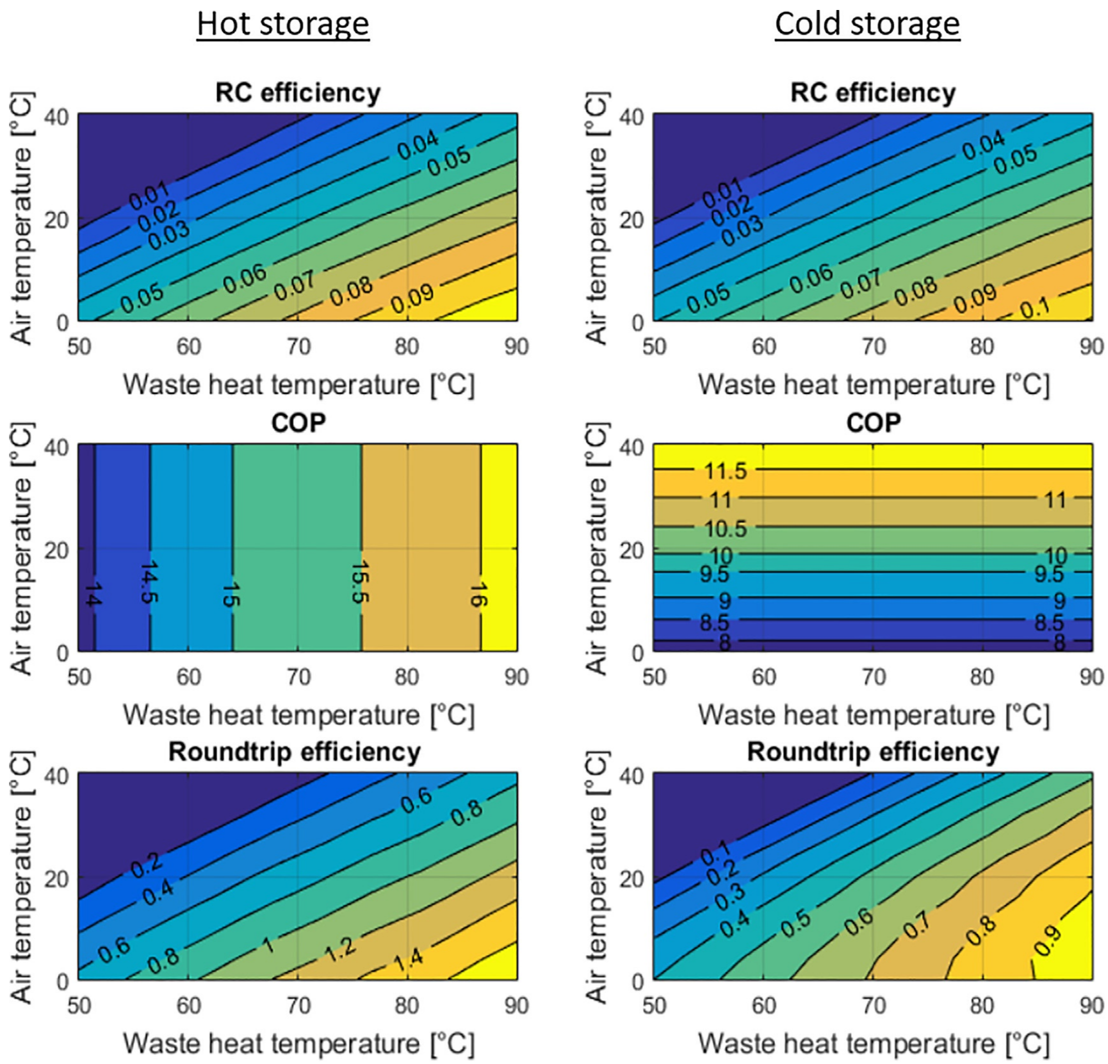

Fig. 5 RC efficiency, heat pump COP and the roundtrip efficiency (glide = 10 K) (Dumont and Lemort, 2020).

As an example, the RC efficiency, the COP of the heat pump and the roundtrip efficiency are shown for a Rankine based PTES in the case of a hot and a cold thermal storages (Fig. 5) (Dumont and Lemort, 2020).

As demonstrated by Eq. (3), the temperature levels do not affect the roundtrip efficiency of a classical PTES. This is why very low temperatures are used for the cold thermal energy storage and high temperatures are encountered for the hot thermal energy storage. Indeed, the efficiency is not affected while the compactness of the global system increases proportionally to the temperature gradient between the two TES (practically, the g factor slightly decreases with the gradient, but this effect is neglected here).

However, this conclusion is not valid for a thermally integrated PTES. Different papers (Francesco et al., 2017; Dumont and Lemort, 2020) have shown that the most important design and control parameter to optimize is the temperature glide. The temperature glide is defined as the increase of temperature provided by the heat pump to the thermal energy storage. Fig. 6 shows T-s diagrams for a high glide on the left (from 65 °C to 85 °C) and for a small glide on the right (from 75 °C to 85 °C) for a hot storage TIPTES.

As mentioned in recent papers (Francesco et al., 2017; Dumont and Lemort, 2020), the glide needs to be optimized in the case of a thermally integrated PTES. Indeed, the lower the glide, 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 Fig. 6). Therefore, a trade-off needs to be found depending on the case study in a way to optimize the system.

Electric heater

It might be interesting to store heat at high temperatures to increase the compactness of the storage system. This may induce a low coefficient of performance (tending to 1) if a heat pump is used for the charging process. Furthermore, heat pumps can hardly reach temperatures above 150 °C. Therefore, it might be relevant to use an electric heater, which is usually simpler than a heat pump

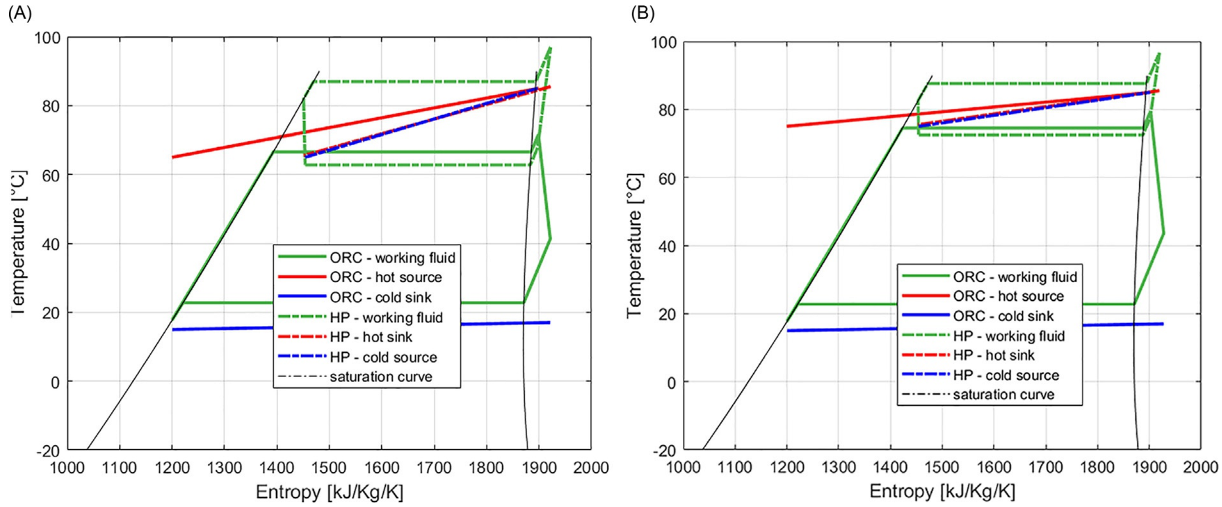

Fig. 6 T-s Diagram for a high glide (left) and a low glide (right).

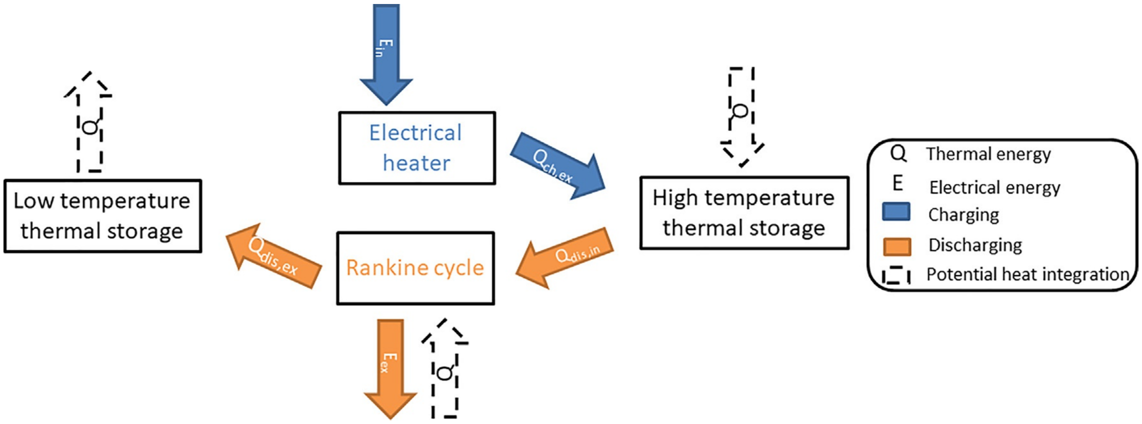

Fig. 7 Electric heater combined with a Rankine cycle.

(Fig. 7). Such storage systems with an electric heater constitute another variant of Carnot battery that can also use an ORC for the discharging mode. Two options have been proposed: the use of an electrical resistance (Siemens, 2019) or the use of a rotating heater (asynchronous machine with permanent magnet using induction). The main advantage of the latter option is that the resistance and the AC/DC converter are not needed compared to the former (Okazaki et al., 2015).

Components mutualization

In order to decrease the capital expenditure, it could make sense to mutualize some of the components of both the vapor compression heat pump system and the ORC power system. The degree of mutualization ranges from the mutualization of a few components (such as the heat exchangers) to almost all components (including the machinery). A mutualized component has to work in both operating modes, meaning that its design does probably not allow to maximize its performance in each single operating mode. As a consequence, the degree of mutualization results from a trade-off between the cost and the performance of the ORC-based PTES. The installed power of the system highly impacts this trade-off.

Mutualization of heat exchangers

Fig. 8 depicts the layout where only the heat exchangers are mutualized (Caraino et al., 2019; Man-es, n.d.). The heat pump (Rankine cycle, respectively) possesses its dedicated compressor (expander, respectively).

Fully "reversible" heat pump/organic Rankine cycle

Many similarities were observed between the components of a heat pump (HP) and the components of an Organic Rankine Cycle (ORC) for small-scale applications (volumetric machines, refrigerants, heat exchangers). Based on this observation, a system able to work as a heat pump or as an ORC with the same components may be conceived (Dumont and Lemort, 2019), i.e. a reversible HP/

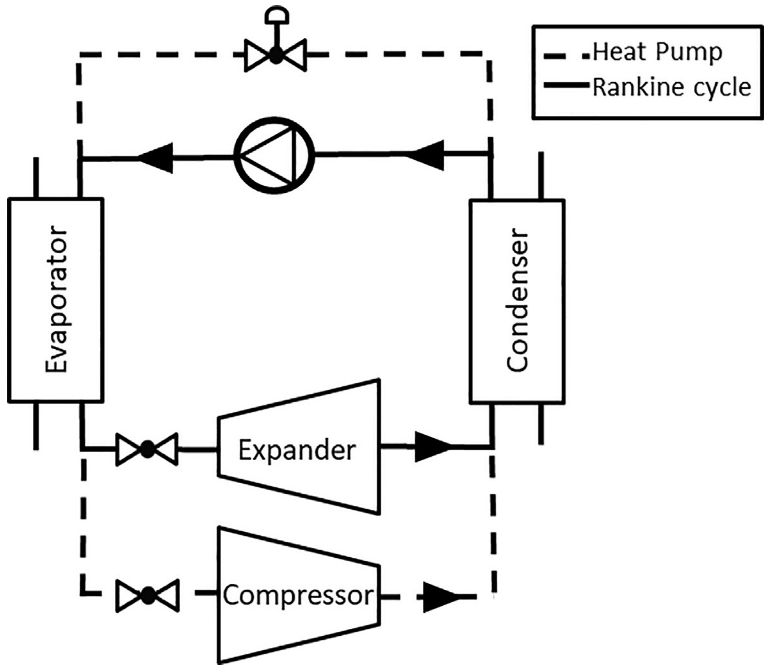

Fig. 8 Mutualization of heat exchangers.

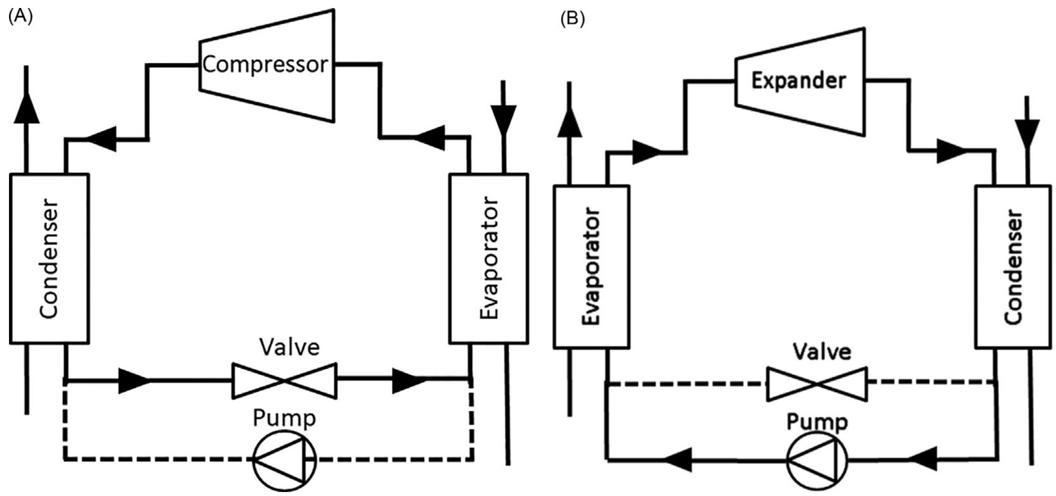

Fig. 9 Example of reversible HP/RC system (left = heat pump mode, right = ORC mode) (Dumont, 2017).

ORC system (Fig. 9). Its application for a small-scale PTES is straightforward and would significantly decrease investments due to the use of a single machine instead of the combination of a heat pump and an ORC power system. Further information can be found about the inherent constraints of the system, the modelling, the optimal sizing and mappings of performance as a function of temperature levels (Lecompte et al., 2015; Dumont and Lemort, 2020). Fig. 9 shows an example where both heat exchangers and compressor are reversible.[1] The feasibility of such a system has already been proven (Dumont et al., 2015, 2020b).

Summary

In summary, a PTES based on ORC can have many different configurations as summarized in Table 1.

[1]The adjective "reversible" has not to be understood from a thermodynamics standpoint. Reversibility means the capacity of the system to invert its operating mode.

Table 1 Possible configurations.

Heating/cooling generator	Heat Pump (heating mode) and Organic Rankine Cycle (HP/ORC) Electric heater + Organic Rankine Cycle (ORC) Refrigerator (cooling mode) and Organic Rankine cycle (R/ORC)
Mutualization of components	No mutualization Mutualization of working fluid and heat exchangers Fully reversible systems (rev. HP/ORC)
Thermal reservoir (in case of TIPTES)	Hot layout Cold layout
Thermal integration	Waste heat recovery (TIPTES) No
Heat pump cycle features	Sub-critical, trans-critical, internal heat exchanger, etc.
Rankine cycle features (Dumont et al., 2018; Macchi and Astolfi, 2016; Lecompte et al., 2015; Dumont and Lemort, 2019)	Subcritical Triangular, flash Transcritical Multiple evaporating pressures
Working fluid	Synthetic fluid Natural fluid Pure and pseudo-pure fluid, zeotropic mixture of fluids
Thermal Energy Storage	Latent (Phase Change Material, Ice) Sensible (water, oil, etc.) hybrid

Technical state-of-the-art

Prototypes

Table 2 presents the different prototypes of PTES using a Rankine cycle that have been developed and were reported in the literature. Since the technology is emerging, many prototypes are being built and this is the reason why this table is also proposed online with continuous updates (Users.Ugent, n.d.). Globally, PTES systems are not mature yet. The CHESTER research project (CHESTER, 2019) investigates the classical configuration (ORC+HP), three research projects concern the use of a reversible HP/ORC (Dumont and Lemort, 2020; AES, 2019; Man-es, n.d.). For the sake of completeness, Table 2 also mentions two large scale units using electric heaters and water as the working fluid (Siemens, 2019).

Key figures

Finally, Table 3 presents the order of magnitude for classical parameters of the PTES. Electric heater configuration is shown apart from the other configurations since this layout works at much higher temperature and therefore presents very different characteristics.

Conclusions and perspectives

This chapter introduces the PTES based on the Rankine technology with different possible configurations, the potential of the technology, existing prototypes and main characteristics in terms of compactness, range of power and efficiency. As already mentioned, the PTES (and more generally the Carnot battery) technology is relatively recent, and many aspects have to be studied in detail. The main challenges to overcome to obtain a complete characterization of the PTES are listed hereunder (Dumont et al., 2020a).

Table 2 Carnot battery based on a Rankine Cycle prototypes (including PTES and systems with electric heater).

Year	*Type*	*Electrical power [kW]*	*Electrical energy [kWh]*	*Working fluid*	*Storage*	*Temp. [°C]*	ϵ_{RT} *[%]*	*References*
2019	TI rev. HP/ORC	2	–	R1234yf	Ice (1 m3)	60	100	AES (2019)
2019	TI rev. HP/ORC	1	10	R1233zd	Water (1 m^3)	90	100	Dumont and Lemort (2020)
2014	Electric heater+ Rankine	700	5000	Water	Rock (40 t)	600	45	Siemens (2019)
2019	Electric heater+ Rankine	1400	12,000	Water	Rock (1000 t)	600	45	Siemens (2019)
2019	ORC+HP	1000	–	R1233zd	Sensible+latent	180	–	CHESTER (2019)
2020	TI Rev. HP/ORC	7500	250,000	CO2	Water	150	–	Okazaki et al. (2015)

Table 3 Main characteristics of the Rankine Carnot Batteries (including PTES and systems with electric heater).

Cycle	*Electric heater and Rankine cycle*	*Heat pump and Rankine cycle*
Power [MW]	Up to 100	Up to 10[a]
Energy [MWh]	Up to 400	Up to 40[a]
Temp. [°C]	Up to 750	Up to 150
Compactness [kW/m^3]	~4	[0.05–1.72]
Compactness [kWh/m^3]	~36	[0.2–207]
EFF [%]	[12–55]	[30–73]/[70–150][b]
Price [$/kW]	~376	[272–468]
Price [$/kWh]	~94	[68–117]
Estimated TRL	9	7
Typical fluids	Water	R1233zd(E),CO_2, NH_3, water
References	Dumont et al. (2020a)	Dumont et al. (2020a) and Benato and Stoppato (2018)

[a]Possible to extend the range by association in series.
[b]Thermally integrated.

- Off-design and part load performance. It is essential to predict and to minimize the degradation of performance in off-design operation (i.e., for different heat sources and heat sinks conditions) and part load regime (i.e., for reduced capacity of the heat pump and ORC).
- System dynamics. The dynamics of the PTES will define the type of flexibility services that could be provided to the electrical grid. Dynamic models calibrated and validated by means of experimental data in transient regime are necessary.
- Integration with other systems. The TIPTES system must be sized and controlled as a function of the characteristics of the waste heat streams (time variations of mass flow rate and temperature, constraints on the cooling of the waste heat stream (for instance to prevent formation of acid condensates), minimal impact of waste heat recovery on industrial process, etc.). Also, the use of the thermal "by-products" (low temperature heat released at the condenser of the ORC during discharging in the hot storage configuration) and the mutualization of the thermal storage for covering part of the on-site heating and/or cooling demands require an in-depth investigation of the integration of the PTES in the building/process. This investigation must account for relevant technical constraints.
- Experimental validation. The PTES is a not a mature technology and many technological developments are expected in the next decade. Models of components and systems calibrated and validated based on experimental data are essential to identify the best components and architecture for a specific application (defined in terms of power, capacity and characteristics of potential integrated heat).
- PTES control. Optimal control strategies must maximize the economic benefit of the PTES depending on the time variations of heat sources and heat sinks characteristics, on dynamic pricing of electricity or on the availability of on-site electricity production. These optimal control strategies must account for technical constraints expressed, among other things, in terms of allowable range of temperatures, pressures and machinery rotating speed. In such a perspective, aforementioned validated dynamic simulation models will be valuable tools for developing such strategies.
- The main advantage of this system compared to an electro-chemical battery is its durability and its low environmental footprint. A life cycle analysis of the system would be necessary to quantify the gains on these aspects (Dumont et al., 2021)
- Techno-economic optimization. The assessment of the economic viability of the PTES is paramount for further development of the technology. Therefore, accurate tools for conducting techno-economic optimization are necessary.

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