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Development of a Compressed Heat Energy Storage System Prototype

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ABSTRACT

Compressed Heat Energy Storage (CHEST) systems are a specific variant of Pumped Thermal Energy Storage systems (PTES) based on the Rankine cycle. The CHEST system described in this work consists of a high-temperature heat pump, a high-temperature thermal energy storage system combining both latent and sensible heat storages, and an organic Rankine cycle system. The use of working fluids with a low global warming potential and zero ozone depleting potential are also considered. In this paper the design and operation modes of a CHEST system concept are presented. A numerical model was developed in TRNSYS software, which served to analyse the system´s capabilities not only as a promising power-to-heat-to-power system able to achieve high electrical roundtrip efficiencies, but also as a highly flexible energy storing system when coupled to a Smart District Heating (DH) installation. Finally, recommendations for the definition of an experimental set-up for the validation of the CHEST concept are provided.

Keywords: High temperature heat pump, thermal energy storage, organic Rankine cycle, power-to-heat-to-power, Carnot battery.

1. INTRODUCTION

Decarbonisation of the energy system is key in order to guarantee the long-term sustainability of the society. Necessary actions should be taken, and ambitious objectives should be defined in order to ensure a secure, sustainable, affordable and competitive energy supply for households and the industrial sector. Achieving this goal will require a fundamental transformation of the energy system itself. Increased integration of renewable energy sources (RES) into the power grids is critical in achieving these specific objectives. However, the biggest challenge for a proper integration of such systems is the discontinuous nature of the generated energy, which makes very difficult to match supply to demand. In order to achieve energy systems based on RES, it is believed that Energy Storage Systems (ESS) will play a relevant role in this transition.

Electrical energy storage for power grids has already proved to be an adequate solution to enhance the reliability and improve grids functionality. ESS are an effective way of storing energy in situations where the energy supply exceeds the demand, making available the stored energy during peak demand periods. The main electrical energy storage technologies available today are the Pumped Hydro Energy Storage (PHES) and the Compressed Air Energy Storage (CAES) systems.

PHES is an already mature and widely used energy storage technique. According to Akhil et al. (2016), it allows to store large amounts of electrical energy in a rather economical way. However, this technology is usually limited by geological constraints, and for a proper implementation it requires a suitable elevation difference in between the pumping system and de water reservoir and a large supply of water.

In CAES systems, the surplus electricity is used to compress air which is stored in a proper reservoir, usually underground storage. When electricity is needed, the stored air is expanded in a turbine in order to generate electricity. However, this kind of systems usually requires consumption of fossil fuels for increasing the turbine´s power and for heating-up the air in order to avoid low air temperatures at the exit of the turbine. Although adiabatic CAES concepts were developed, the major drawbacks of this technology are geographical restrictions and environmental concerns due to the need of sufficient underground storage and the use of fossil fuels in the discharging process (Lindeman et al., 2018).

Other technologies that have been used as an ESS are the thermo-mechanical storage systems. In such systems, surplus electricity is used to generate high temperature heat, which is used to charge a thermal energy storage. When electricity is required, the stored heat is used to drive a thermal power cycle obtaining electricity during the discharging process. For these systems, the maximum roundtrip efficiency, which is the ratio of the net output power to the total input power, that can be achieved is defined by the Carnot efficiency. Due to exergetic losses, real systems usually can reach values in the range of 40%. However, an alternative thermo-mechanical storage system in which during the charging phase the surplus electricity is used to increase the temperature level of a heat source, can be considered. In the discharging process, heat from the storage is used to operate a thermal power cycle. Systems based on this concept are called Pumped Thermal Energy Storage (PTES) systems, which were thoroughly analysed by Jockenhöfer et al. (2018). Figure 1 shows the working principle of a PTES cycle.

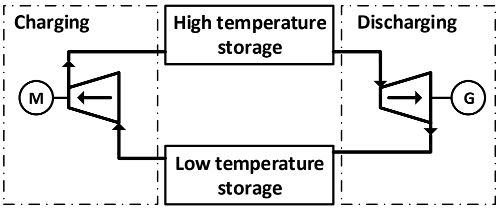

Figure 1: Working principle of a Pumped Thermal Energy Storage (PTES).

According to Jockenhöfer et al. (2018), when implementing systems based on the PTES concept, the attainable efficiency is no longer limited by the Carnot efficiency, and roundtrip efficiencies of up to 100% can ideally be achieved.

$$\eta_{roundtrip} = \frac{electrical\ energy\ generated\ during\ discharging\ process}{electrical\ energy\ consumed\ during\ charging\ process}$$

Furthermore, some PTES systems allow for the integration of low temperature heat sources, typically delivered as waste heat from industrial processes, solar thermal or geothermal systems or data centre cooling installations. When using low temperature heat as heat source (thermal energy integration in PTES), the compression work during the charging process can be reduced. If the temperature difference of the system´s heat source and heat sink is sufficiently large, the work delivered during the discharging process might even exceed the compression work required during the charging process. Figure 2, presents a basic diagram of this concept.

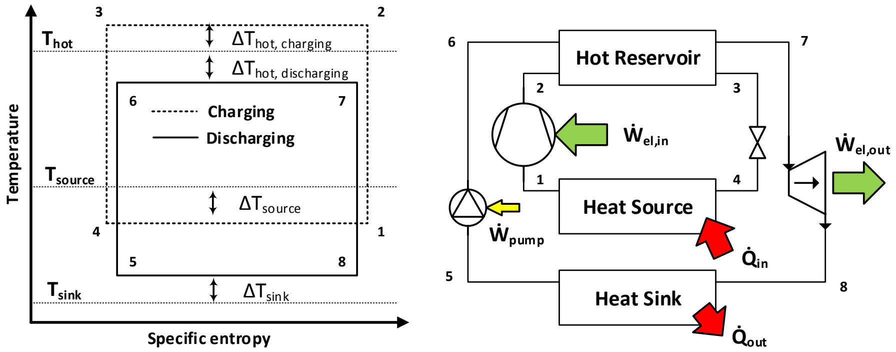

Figure 2: Carnot-based model of a heat-integrated PTES cycle.

When considering PTES systems with thermal energy integration, a different notation for the system´s electrical roundtrip efficiency will be considered. Hereby, the roundtrip effectiveness is introduced as $\varepsilon_{roundtrip}$.

$$\varepsilon_{roundtrip} = \frac{electrical\ energy\ generated\ during\ discharging\ process}{electrical\ energy\ consumed\ during\ charging\ process\ with\ integrated\ heat\ source}$$

In this kind of applications, if additional exergy is transferred to the system at the heat source level, the value of $\varepsilon_{roundtrip}$ might thereby exceed 1.0, which in contrary is not attainable for $\eta_{roundtrip}$.

The main objective of this study is to present a comprehensive analysis of a specific variant of a PTES system based on the Rankine cycle. The system described in this work consists of a high-temperature heat pump, a high-temperature thermal energy storage system (combining both latent and sensible heat storages) and an organic Rankine cycle system. A numerical analysis of the whole system was implemented in order to define the system´s minimum design requirements, as well as to evaluate the expected operational performance and thereby validate its ability of storing electric energy with a roundtrip effectiveness ($\varepsilon_{roundtrip}$) of 100% or higher. Finally, recommendations for the design of an experimental set-up for the validation of the heat-integrated PTES cycle are going to be presented.

2. THE CHEST CONCEPT

2.1. General description

The PTES system presented in this work is a combination of Rankine cycles activated with electricity using latent and sensible heat storage systems, defined first by Steinmann (2014) as Compressed Heat Energy Storage (CHEST) system. The CHEST system operates with two Rankine cycles using a latent heat storage as an intermediary stage between the two cycles.

The operation of the system starts by charging the latent thermal energy storage (LH-TES) at high temperature. This is achieved using a high temperature heat pump (HT-HP) system equipped with an electric powered compressor. The HT-HP operates using surplus electricity available in the power grid during low power demand periods. The heat source for the heat pump is provided from renewable sources (or from recovered waste heat). During the charging phase of the LH-TES, a sensible thermal energy storage (SH-TES) is also charged by the heat pump to optimize the cycle´s performance during partial load operation. Heat is stored in both the LH-TES and the SH-TES until there is a demand in the power grid. During power demand the heat from the SH-TES is used as a pre-heater of an organic Rankine cycle and the heat from the LH-TES is used in its evaporation process. The expander of the ORC generates electricity which is delivered back into the grid (the integration of an ORC system into a Carnot battery was analysed in detail by Pillai et al., 2019).

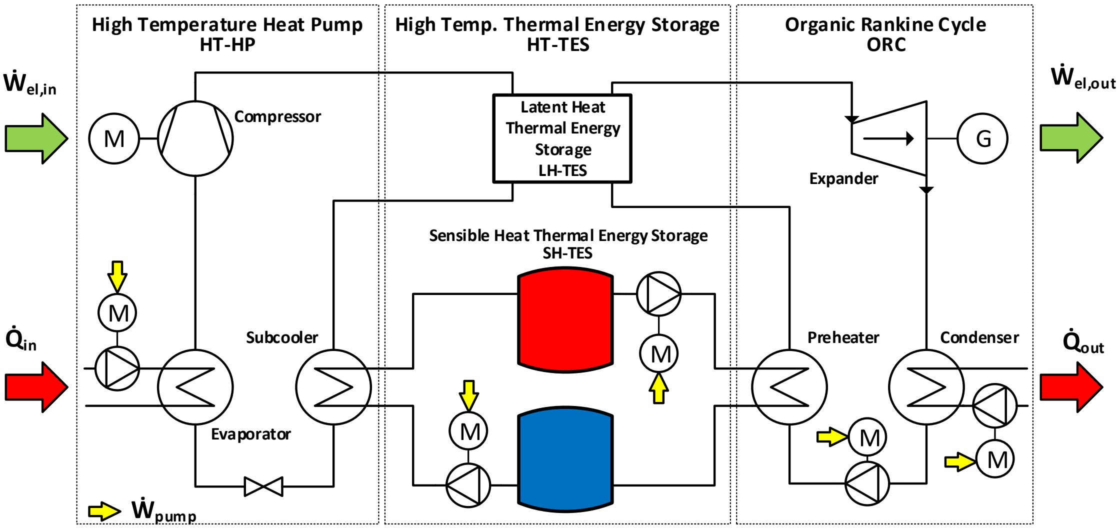

Figure 3: Conceptual diagram of the CHEST concept.

2.2. Operating modes.

One of the key features of the CHEST concept, which clearly makes a difference from other systems, is its high flexibility, which allows to efficiently respond under different boundary conditions and energy needs. The CHEST concept, when integrated into Smart DH systems, offers a variety of operation modes that can be actively chosen (see Figure 4).

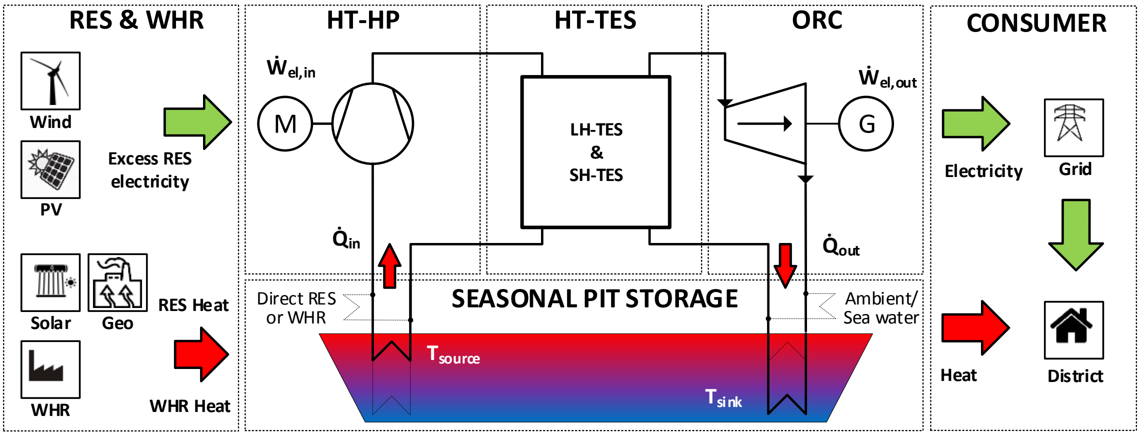

Figure 4: CHEST concept integrated into a smart DH.

Depending on the current state of boundary conditions, it offers the possibility to convert more heat into power, or more power into heat. Within this study, a total of six different operating modes were proposed.

It can be appreciated that surplus electrical energy from RES (i.e.: from wind or photovoltaic (PV) fields) can be supplied to the HT-HP while heat from a seasonal pit storage is used as the HT-HP heat source. The pit storage is charged by heat from solar thermal fields or industrial waste heat recovery (WHR) systems. Then heat is upgraded from the upper level of the seasonal pit storage (or directly from RES/WHR systems) by the HT-HP and accumulated at a higher temperature in the HT-TES. When required, the ORC system can generate electricity that will be redirected to the power grid, while heat is dissipated back into the seasonal pit storage system (or directly to the ambient). Table 1, summarizes the six operating modes that were defined for the evaluation of the CHEST concept.

Table 1. Operating modes characteristics.

	T_{source}	T_{sink}	$\dot{W}_{el,in}$	$\dot{W}_{el,out}$	$\dot{Q}_{in}$	$\dot{Q}_{out}$	**Source**	**Sink**
	ºC	ºC	MWel	MWel	MWth	MWth		
Mode 1	80	40	1	0.66	5	5.33	Upper part of DH storage	Lower part of DH storage
Mode 2	80	10	1	1	5	5	Upper part of DH storage	Ambient air or sea water
Mode 3	100	40	1	1	7	7	RES/WHR at 100ºC	Lower part of DH storage
Mode 4	100	10	1	1.5	9	8.5	RES/WHR at 100ºC	Ambient air or sea water
Mode 5	60	60	1	0.3	2.3	3	Upper part of DH storage	Upper part of DH storage (charging)
Mode 6	40	60	1	0.2	2	2.8	Lower part of DH storage	Upper part of DH storage

3. NUMERICAL SIMULATION

A thermodynamic model for the representation of the CHEST concept was developed in the TRNSYS simulation environment. The main description of the model, the definition of different scenarios that were evaluated and the main results achieved within the numerical analysis are presented in the following sections.

3.1. Model description

Figure 5, shows the graphical representation of the TRNSYS model used in this analysis which is divided in six main sections, the heat source (RES), the pit storage, the HT-HP, the HT-TES, the ORC and the power load (consumer).

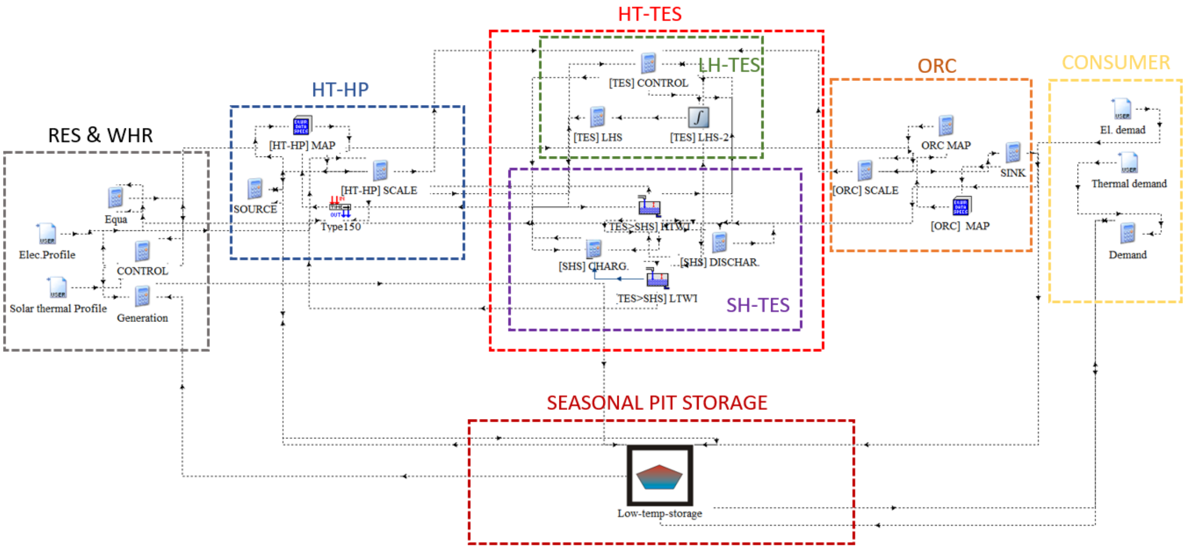

Figure 5: TRNSYS model of the CHEST concept based on performance maps.

The HT-HP performance is evaluated using performance maps obtained with Engineering Equation Software (EES) and applying scaling factors to adapt the outputs of the map to the conditions of the simulation (adjustment of the HT-HP´s capacity). The ORC performance is also obtained by the interpolation inside EES generated performance maps and scaling factors. A simplified adiabatic model is implemented to calculate the energy stored and the state of charge of the LH-TES tank, while the SH-TES system is simulated using two adiabatic variable volume storage tanks containing water at two different temperature levels. A Phase Changing Material (PCM) with a design melting temperature of 133 ºC was considered for the LH-TES. In terms of working fluids, the refrigerants Butene and R1233zd(E) were used in the analysis, being both refrigerants considered environmentally friendly gases.

Within the model, the RES electricity production and electricity demand can be provided from an external file. The nominal power (electrical capacity) of the HT-HP and ORC, the maximum capacity of the HT-TES system (both, the LH-TES and SH-TES), the system´s source and sink temperatures and the desired control strategy can be defined by the user. For the simulations it was assumed that there are no heat losses to the ambient in the HT-TES system, that the internal temperature distribution within the LH-TES is uniform and a water temperature setpoint of 133 ºC in the upper tank of the SH-TES..

In terms of control strategy, the model has been developed in order to check that the behaviour of the system is consistent. Therefore, the model is able to control the power entering the HT-HP (or to be produced by the ORC), the load conditions for both the HT-HP and ORC, the level of charge of the SH-TES and LH-TES tanks, as well as the temperatures of the SH-TES tanks for the correct functioning of the equipment.

3.2. Evaluated scenarios

The TRNSYS simulation tool was applied to the six modes considered before, in order to validate the CHEST concept under the different boundary conditions. The results provided the specifications and requirements of each of the system´s components. Furthermore, three different scenarios were defined in order to cover the needs depending on energy availability and demand requirements over the year. These scenarios are profiles that will represent the energy availability and demand (both, electrical and thermal) over these periods. The structure for each scenario, as well as the operation strategy that each scenario will intend to represent, can be seen in Table 2.

Table 2. Available energy and demand for different seasons.

Season	Available energy			Energy Demand			Operating strategy
	PV	Solar	Wind	Heat	Elect.	Re-charge*	
Summer	High	High	Medium	Low	High	Medium	Storage of electric energy (mainly).
Winter	Low	Low	High	High	High	---	Heat and electricity. Can provide domestic heat.
Transitional	Medium	Medium	Medium	Medium	High	Low	Heat and/or electricity. *Re-charge of pit storage.

For each scenario (summer, winter and transitional period) a design month profile has been defined in order to carry out the first approach of the system components sizing. Based upon the six operation modes defined for the evaluation of the CHEST concept operation, a total number of 29 case studies have been defined in order to evaluate the performance of the system under different operating conditions and sizing combinations of the main components (See Table 3).

Table 3. Definition of the case studies.

	Case	Season	Elect. E. Ratio	Size of the system				T_{source}	T_{sink}
			Supply/Demand (MWh/MWh)	HP (MW)	ORC (MW)	SH-TES (m^3)	LH-TES (MWh)	(ºC)	(ºC)
Mode 1	1.1	Transitional	1,2	1	1	300	30	75-78	40-45
	1.2	Transitional	1,2	1	2	300	30	75-78	40-45
	1.3	Transitional	1,2	2	1	300	30	75-78	40-45
	1.4	Transitional	1,2	2	2	300	30	75-78	40-45
	1.5	Transitional	1,2	2	1	600	60	75-78	40-45
	1.6	Transitional	1,2	2	1	300	60	75-78	40-45
	1.7	Transitional	1,2	2	1	600	30	75-78	40-45
Mode 2	2.1	Transitional	1,2	2	1	300	30	75-78	10
	2.2	Transitional	1,2	2	1	300	30	75-78	15
	2.3	Transitional	1,2	2	1	300	30	75-78	17,5
	2.4	Transitional	1,2	2	1	450	45	75-78	10
	2.5	Transitional	1,2	2	1	600	60	75-78	10
	2.6	Transitional	1,2	2	1	300	15	75-78	10
	2.7	Transitional	1,2	2	1	450	30	75-78	10
	2.8	Transitional	1,2	2	1	600	30	75-78	10
Mode 3	3.1	Transitional	1,2	2	1	300	30	100	40-45
	3.2	Transitional	1,2	2	1	300	15	100	40-45
	3.3	Summer	1,2	2	1	300	15	100	55
	3.4	Summer	1,2	2	1	600	30	100	55
	3.5	Summer	1,2	2	1	300	15	100	40
Mode 4	4.1	Summer	1,75	2	1	300	15	100	10
	4.2	Summer	1,75	2	1	600	30	100	10
Mode 5	5.1	Winter	0,8	1	1	300	15	55	55
	5.2	Winter	0,8	1	1	150	15	55	55
	5.3	Winter	0,8	1	1	100	10	55	55
	5.4	Winter	0,8	1	1	100	7,5	55	55
	5.5	Winter	0,8	1	1	75	5	55	55
Mode 6	6.1	Transitional	1,2	1	1	300	30	40	60
	6.2	Transitional	1,2	1	1	200	20	40	60

3.3. Results

The ability of the CHEST concept of storing electric energy with an appropriate roundtrip effectiveness was evaluated. Figure 6, shows the $\varepsilon_{roundtrip}$ achieved for all the cases that were considered in this study. It can be appreciated that, depending on the operating mode that´s being simulated, the resulting ratio could be as low as 12% (i.e.: Mode 6) or it can even reach values higher than 160 % (i.e.: Mode 4). As expected, the parameters that will greatly define the achievable effectiveness are the source and sink temperatures. Thereby, the highest $\varepsilon_{roundtrip}$ values were achieved when T_{source} is high (100 ºC) and T_{sink} is low (10 ºC), while the lowest values were achieved with a T_{source} of 40 ºC and a T_{sink} of 60 ºC.

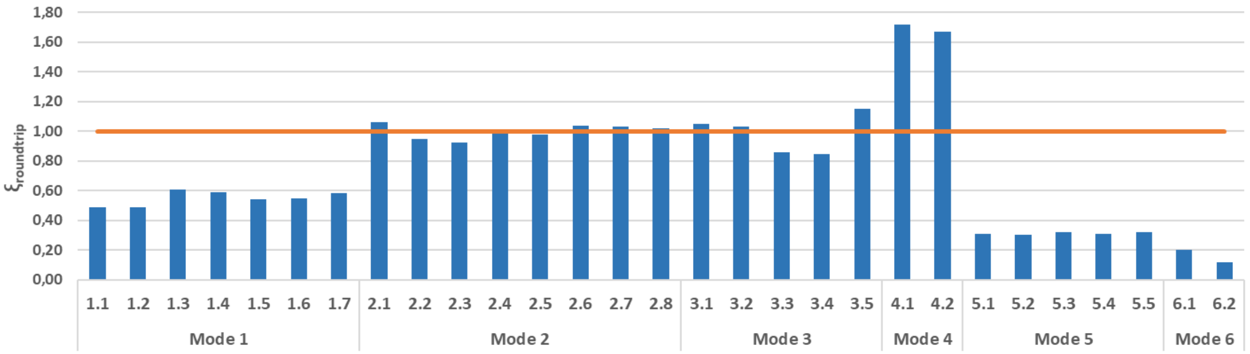

Figure 6: Roundtrip effectiveness for the different case studies.

Regarding the generation of electricity by means of the ORC system, Figure 7 shows the ratio between the electricity generated by the ORC versus the demand. For a particular operating mode, the bigger the HT-TES size (both, the SH-TES and the LH-TES), the more electricity will be generated by the ORC.

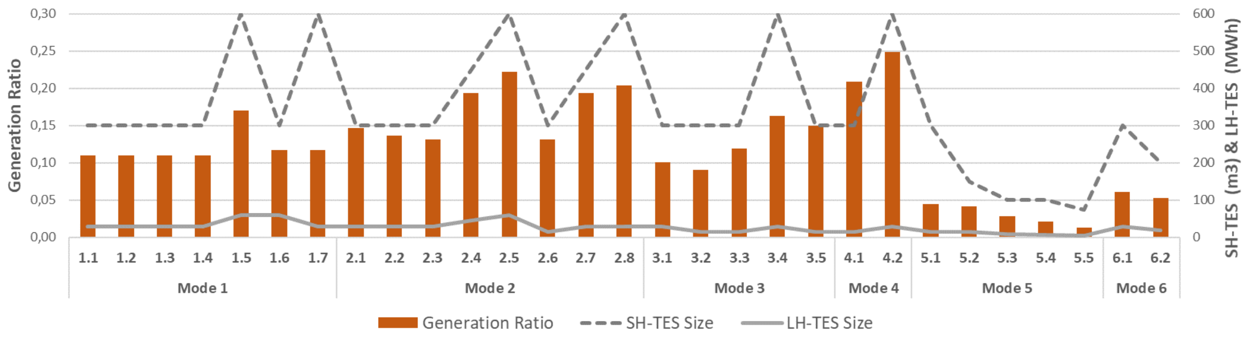

Figure 7: Generation Ratio, SH-TES and LH-TES sizes.

In this kind of applications, an increase of the generated electrical energy is desirable. However, increasing the electrical energy output means that more energy from the heat source will be required, which in this particular case means that more heat will be extracted from the DH´s seasonal pit storage. If not enough heat from RES is provided to this storage system, the temperature level of the storage will consequently decrease. When evaluating the thermal level of charge of the HT-TES storage system (See Figure 8), it was observed that sizing of the storage systems is crucial. If are not sized properly a disproportional level of charge could happen between the LH-TES and the SH-TES, so when one of the storages reaches a fully charge (or fully discharge) condition, the other still could be at an intermediate level.

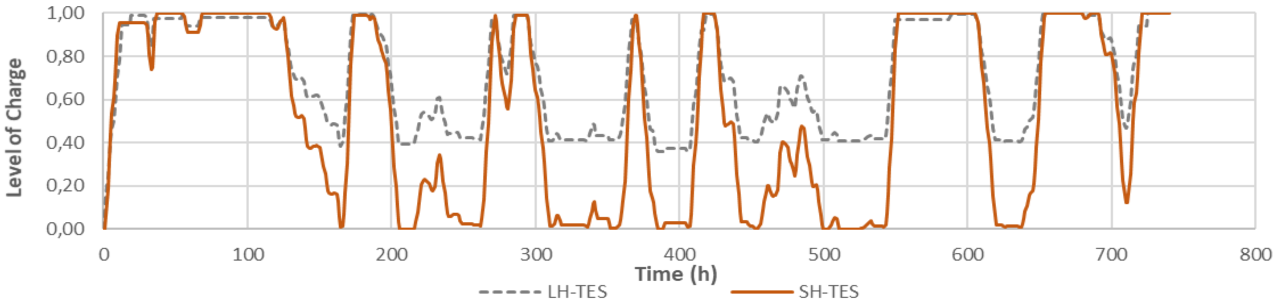

Figure 8: HT-TES level of charge (Case 2.4).

Figure 9, presents the ratio of the electricity that the HT-HP was not able to consume (due to its size restriction) in respect to the available RES electrical energy (excess electricity ratio). It can be concluded that, for the simulated conditions, if the HT-HP size was fixed at 1 MW_{el}, approximately 12 to 15 % of the available RES electricity was not used. When the size of the HT-HP is doubled, almost all the available electricity was consumed by the system (Cases 1.3 to 3.5). However, in Mode 4 a higher excess electricity ratio was also obtained even if the HT-HP size was also twice as big as the ORC system. This is explained because in this mode a higher electrical energy ratio is considered (See Table 2), which means that more RES electricity was available in this operating mode in comparison to the other operating modes, therefore, the HT-HP "struggled" to consume all the electricity that was available from renewable energy sources.

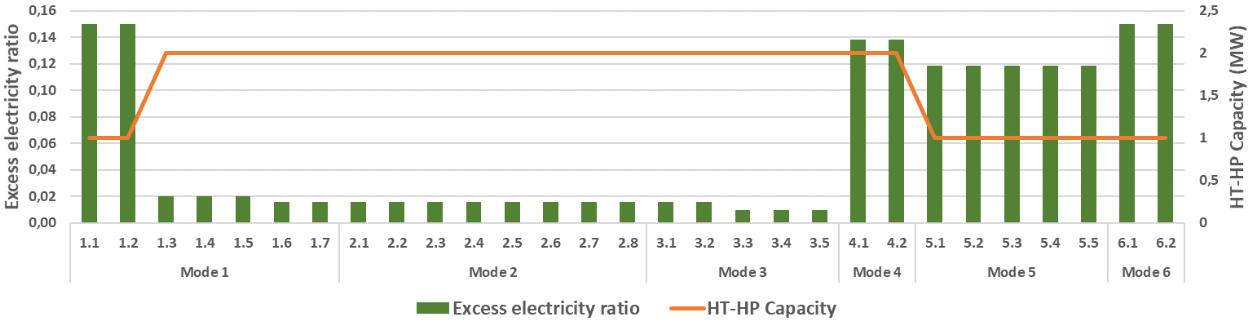

Figure 9: Excess electricity ratio and HT-HP capacity.

3.4. Development of a future experimental set-up

The analysis that was conducted has served to validate that systems based on the CHEST concept could provide excellent capabilities not only as a promising power-to-heat-to-power system, being able to achieve high electrical roundtrip effectiveness values, but also as a highly flexible system when coupled to a Smart DH system. However, an experimental validation of the behaviour of this kind of system seems to be necessary in order to acquire a better knowledge of the system´s dynamic behaviour over several operating conditions. Therefore, the following general recommendations are provided for the development of a full CHEST system prototype:

- In order to achieve a good validation of the CHEST concept and to evaluate different operation modes, the heat source system should be able to provide hot water in a range from 40-60ºC up to 100ºC. The heat sink system must be able to absorb heat from the ORC's condenser in a aproximate temperature range of 60ºC to 10ºC.
- To evaluate the influence of the sizing of the main components on the operation of CHEST system, the experimental set-up should be able to provide the possibility to evaluate different capacities and level of charge for the LH-TES and the SH-TES (by implementing, for example, independent external heating and/or cooling systems for these systems), and operate the HT-HP and the ORC systems over a wide range of thermal and electrical capacities.
- The active technologies, namely the HT-HP and ORC systems, must be able to operate in part load conditions in order to achieve a full validation of the charging and discharging procedures of the CHEST system. It is believed that both technologies should be capable of adapting their operation considering the dynamic behaviour expected in terms of the heat transfer that will take place within the LH-TES.
- Environmentally friendly refrigerants should be considered, such as the fluids used in this analysis (Butene and R1233zd(E)). However, further analysis already shows that other promising refrigerants for this application could be the refrigerants R1224yd and R1336mzz(E) (adequate when considering a PCM melting temperature of 133ºC and for small-scale compressors and/or expanders).

4. CONCLUSIONS

ESS will play a relevant role in the integration of RES into power grids. As one of the promising ESS technologies, PTES systems are known for their potential of storing large amounts of electrical energy without geographical restrictions. However, and due to inefficiencies in the processes of energy transformation, the maximum ideal electric round-trip efficiency that can be achieved with these systems is 1. If what is sought is to maximize electrical efficiency, PTES systems with integration of low temperature heat is a promising way to compensate for those inefficiencies and, therefore, increase ESS performance. This study focussed in the analysis of a particular heat-integrated PTES system based on the Rankine cycle. These particular PTES variant has been denominated Compressed Heat Energy Storage (CHEST) system.

A dedicated TRNSYS model was developed and used to analyse the behaviour of the CHEST concept under different scenarios. Six different operating modes were considered for validating the CHEST concept. It was confirmed that this kind of systems might offer high flexibility as a power-to-heat-to-power system, providing a solution that seems to be able to efficiently respond under different boundary conditions and diverse RES integration scenarios. The ability of CHEST systems for storing electrical energy was analysed and the results confirmed that this kind of technology could operate with electrical roundtrip effectiveness values higher than 100 %. However, special attention must be put in the system´s sizing. According to the results, it seems recommendable to consider a HT-HP with an electrical capacity twice as large as the one defined for the ORC system. Regarding the HT-TES, providing a large heat storage capacity maximizes the capabilities of the system to generate electricity (when the HT-TES doubles its size, the generated electrical energy by the ORC was increased in a range between 30 to 50 %, approximately). However, a proper sizing ratio in between the LH-TES and the SH-TES should always be considered. It can be observed that a sizing ratio in between the SH-TES to the LH-TES of 10 m^3/MWh of storing capacities seems to provide the best results.

Finally, general design recommendations were provided for the development of a laboratory-scale prototype that will be used to experimentally validate the behavior of a CHEST system integrated in a Smart DH. Guidelines were provided in relation to the appropriate operating range considered, the impact of the main components sizing on the operation of the system, and in terms of the working fluids adopted.

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NOMENCLATURE

CAES	Compressed Air Energy Storage	*CHEST*	Compressed Heat Energy Storage
DH	District Heating	*ESS*	Energy Storage Systems
EES	Engineering Equation Solver	ε	Effectiveness
η	Efficiency	*HP*	Heat Pump
HT	High Temperature	*LH*	Latent Heat
ORC	Organic Rankine Cycle	*PCM*	Phase Changing Material
PV	Photovoltaic	*PTES*	Pumped Thermal Energy Storage
PHES	Pumped Hydro Energy Storage	$\dot{Q}$	Heat flow (MW)
RES	Renewable Energy Source(s)	*SH*	Sensible Heat
T	temperature (K)	*TES*	Thermal Energy Storage
TRNSYS	Transient System Simulation Tool	$\dot{W}$	Electrical Power (MW)
WHR	Waste Heat Recovery		

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