CHESTER

Compressed Heat Energy
Storage for Energy
from Renewable sources

# D2.4 Requirements of individual technologies that form the CHEST system

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# Glossary, abbreviations and acronyms

| | |
|---|---|
| CHEST | Compressed Heat Energy Storage |
| DH | District Heating |
| HP | Heat Pump |
| HT-HP | High temperature heat pump |
| HTTES | High temperature thermal energy storage |
| LH-TES | Latent heat thermal energy storage |
| ORC | Organic Rankine Cycle |
| PCM | Phase change material |
| SH-TES | Sensible heat thermal energy storage |
| TES | Thermal energy storage |
| TRNSYS | Transient System Simulation |
| $T_{melt}$ | Melting temperature |

# 1 Introduction

## 1.1 Purpose and Scope

The aim of this deliverable is to define, analyse and evaluate the requirements of the individual technologies that form the CHEST system; a high temperature heat pump (HT-HP), an organic Rankine cycle (ORC) and a thermal energy storage (TES), which in turn consists of latent (LH-TES) and sensible (SH-TES) heat thermal energy storage systems.

A dedicated CHEST system simulation model has been implemented. This model consists of an upgraded version of the TRNSYS model previously developed in Task 2.2, in which the simulation of the main technologies that form the system has been decoupled one from each other in order to provide a more robust and flexible simulation tool for the analysis of the behaviour of the CHEST concept.

One of the key features of the CHEST concept is the high flexibility it offers in terms of adjusting its operational mode to different boundary conditions and needs. Within this deliverable, six different operation modes are considered, which depending on the current state of boundary conditions, will offer the possibility to the system to convert more heat into power, or more power into heat.

The simulation tool developed within this deliverable was applied to each one of the six simulation modes considered for the CHEST system. The main purpose of this analysis was to theoretically validate the operation of the CHEST concept under different boundary conditions, while providing relevant information that will be used in WP3 in the design of the individual technologies that form the CHEST system.

Finally, the model developed within this deliverable will serve as the baseline of the full-scale CHEST system model that will be developed in WP4.

## 1.2 Structure of the document

The document is divided in five main sections.

First, in Section 2.1, a brief description of the CHEST concept is presented to then explain the different working modes that can be actively chosen depending on the boundary conditions.

The next section describes the upgraded TRNSYS model developed in order to identify the specifications of individual components (Section 3). Within this description, main variables are explained as well as the control strategy and the outputs.

Therewith, the different working modes of CHEST system, described in previous sections, are simulated with their particular boundary conditions for a preliminary assessment of the components using the TRNSYS model explained before (Section 4).

Finally, after the analysis of the CHEST components under the different boundary conditions and needs, general and technical conclusion can be drawn (Section 5).

# 2 CHEST Concept

## 2.1 Description of the Concept

The CHEST system is based on an advanced concept for indirect thermo-mechanical storage of electrical energy. It converts electrical energy and low-temperature heat to high temperature heat via a heat pump. The high temperature heat is stored and, upon request, converted back to electrical energy by a power cycle (Figure 1).

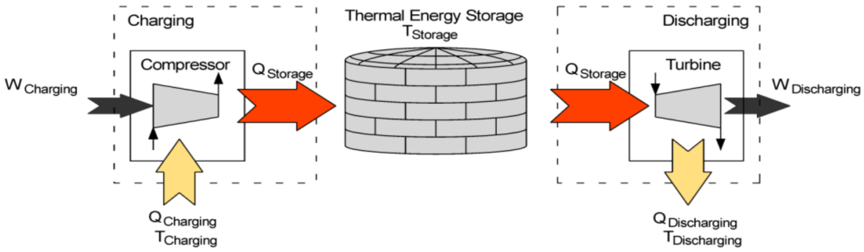


*Figure 1: Basic concept of thermo-mechanical energy storage.*

Such a system can not only be used to store electrical energy. During discharging, the system provides simultaneously both electrical and thermal energy, which can be used for domestic or process heating. The flexibility can be further increased by the integration of renewable or waste heat at an adequate temperature level, so the power required by the heat pump can be reduced. In this case the power delivered during discharge might exceed the power fed into the system. The CHEST system is a powerful concept to efficiently integrate various sources of renewables, taking advance of the synergies between them (Figure 2).

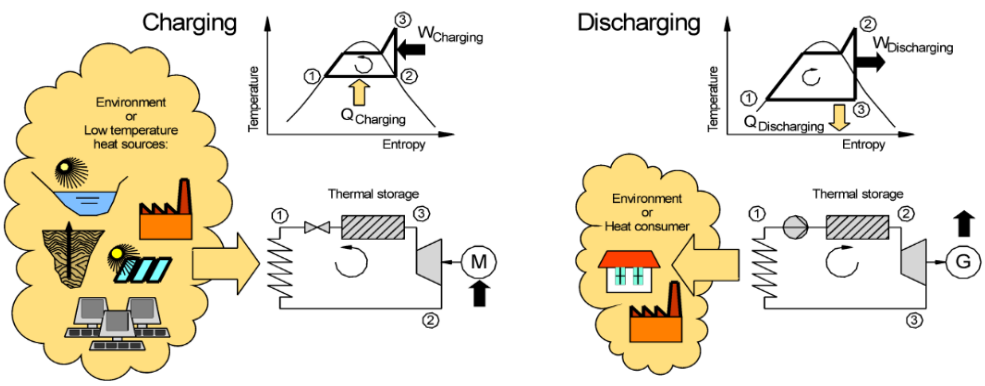


*Figure 2: CHEST with utilization of both heat and power during charging and discharging.*

## 2.2 Working mode description

In this section, six different operation modes will be described. For example, on a winter weekend when only little electrical energy is needed by the industrial sector, but a lot of wind energy is available and heat demand of the district heating is high, mode 5 o 6 can be chosen. However, in summer on working days with high demand of electrical energy, little demand of district heating and a lot of solar thermal energy available, mode 3 or 4 can be chosen.

Each one of the six working modes considered in this analysis are described here below:

**Working mode 1 or regular mode** represents the operation mode of the CHEST system in spring, autumn or winter when the DH needs heat production as well as electricity (Figure 3). The CHEST system consumes 1 MWel during charging and delivers 0.66 MWel discharging, assuming 80 $^{o}$C as evaporation inlet temperature and 40 $^{o}$Cas condensation inlet temperature.

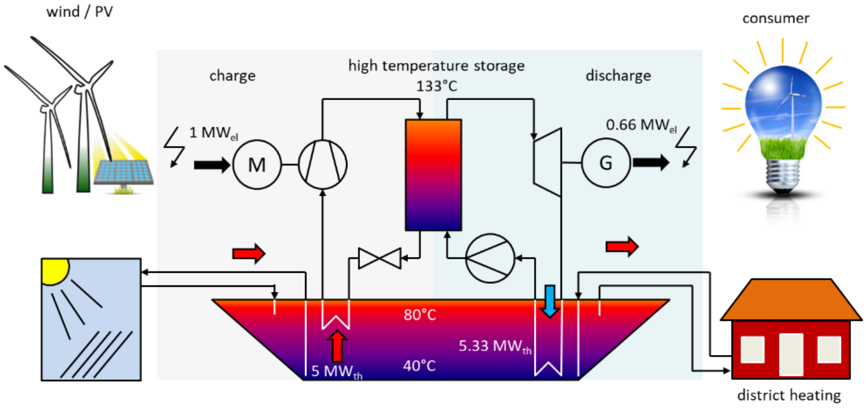


*Figure 3: Proposed working mode 1.*

**Mode 2** will be suitable if higher round trip efficiency is needed, of 100 % (Figure 4). This operation mode can be achieved by reducing the temperature of the ORC heat dissipation (condenser inlet temperature) to 10 $^{o}$C using sea water or ambience as heat sink to reject this heat.

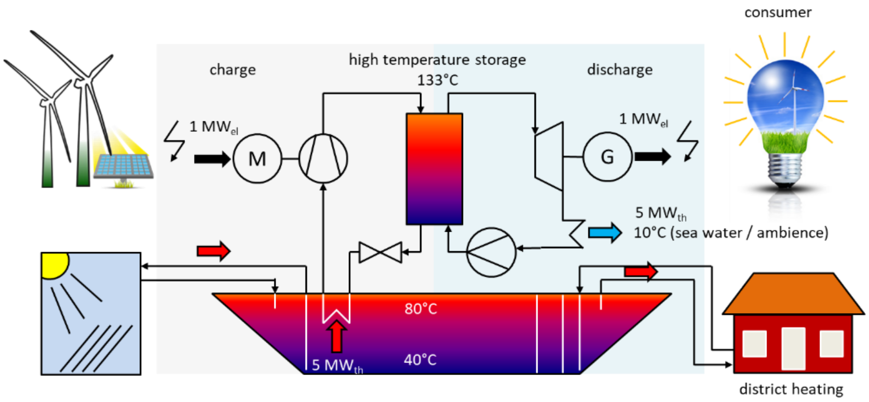


*Figure 4: Proposed working mode 2.*

**Working mode 3**: This working mode is also suitable if a higher round trip efficiency is required. This can be achieved by changing the boundary conditions, for example by selecting a RES source with a higher temperature up to 100 °C, as can be seen in Figure 5.

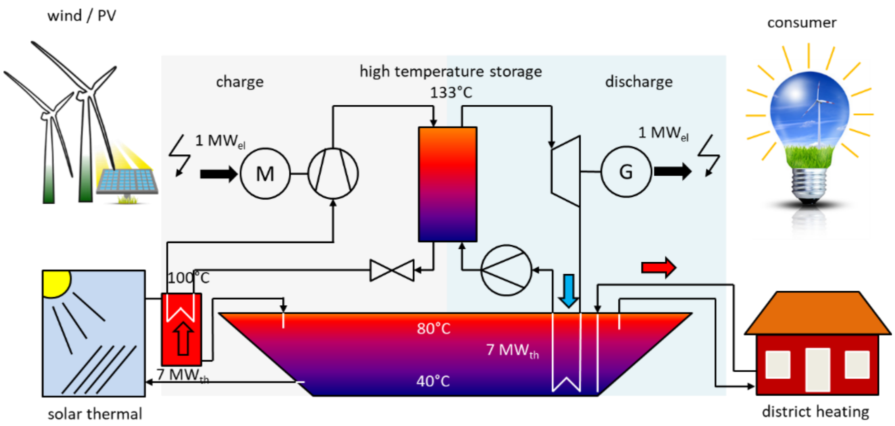


*Figure 5: Proposed working mode 3.*

Operation **mode 4**, is a combination of mode 2 and 3 (Figure 6). The round trip efficiency is higher than 100%. For 1MWhel that the system consumes, it can deliver 1.5 MWhel when it is needed. For example, at summer time when little demand of DH is needed, and a lot of solar thermal energy is available.

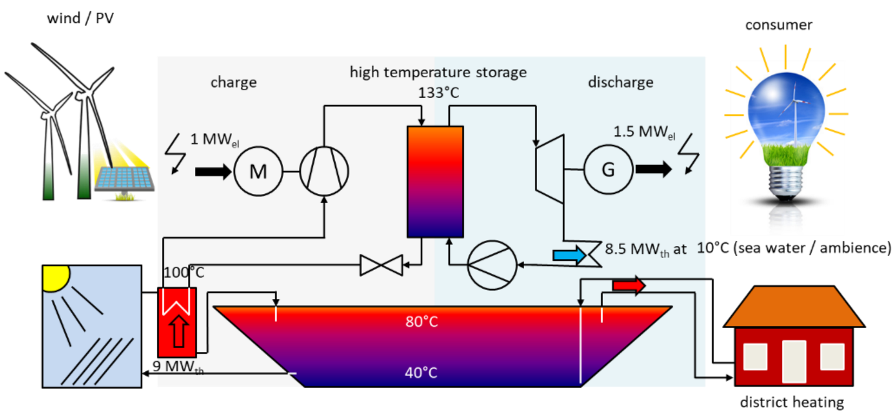


*Figure 6: Proposed working mode 4.*

Operation **mode 5**, is suitable for winter time. It provides low round trip efficiency (30%) but increases the temperature of the seasonal thermal energy storage, heating it. For each MWhel that the system consumes, 0.7MWhth will be converted into heat (Figure 7).

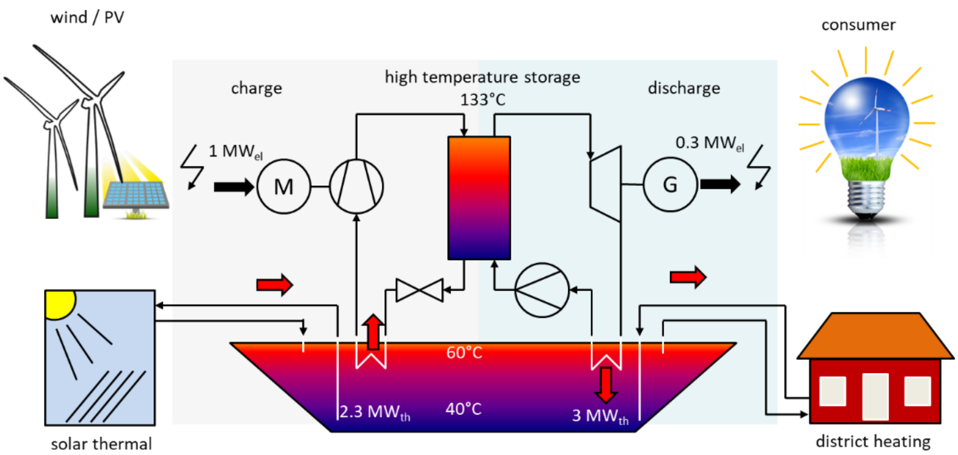


*Figure 7: Proposed working mode 5.*

**Operation mode 6,** or heat pump mode, is similar to operation mode 5, but with a stronger heating of upper layer of the seasonal TES at lower round trip. It is suitable for weekend or transitional periods, when only little electricity energy is needed by industry, but a lot of wind energy is available and heat demand of the district heating is needed (Figure 8).

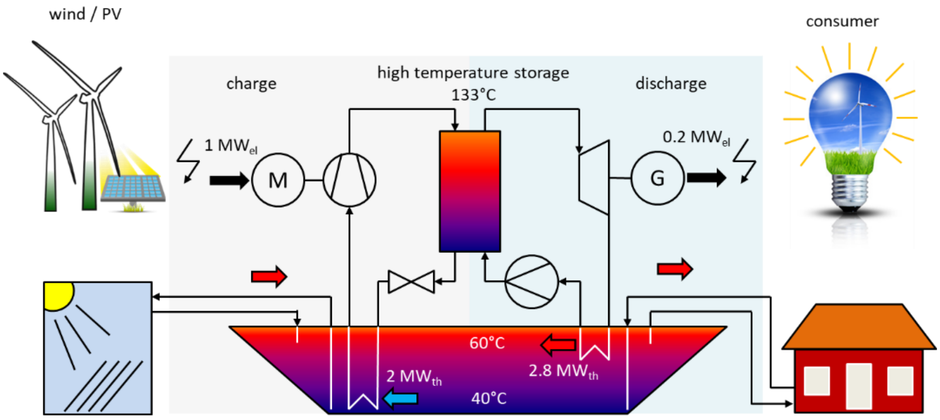


*Figure 8: Proposed working mode 6.*

# 3 TRNSYS Simulation Model

The main objective of task 2.4 is to define the requirements of individual technologies of the CHEST system. This is done by upgrading the TRSNSYS model developed in task 2.2. In order to identify the specifications of individual components, a decoupled model has been developed. This decoupling provides more flexibility to the model and allows analysis at component level as well as system level.

In this section, a general scheme of the proposed model, with the different sub-systems, is presented. The complete TRNSYS-CHEST model is depicted in Figure 9.

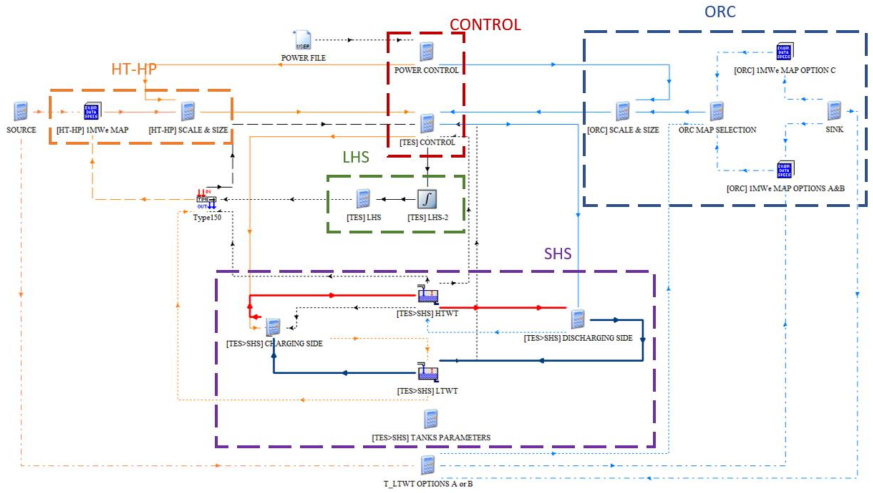


*Figure 9: TRNSYS CHEST model.*

As inferred from Figure 9, there are five differentiated blocks that interact with each other:

- CONTROL: includes different control strategies
- HT-HP: in this block 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).
- ORC: the performance of the ORC is also obtained by the interpolation inside EES generated performance maps and scaling factors. In this case, two different maps can be employed depending on the selected method for the calculation of the outlet temperature of the ORC´s preheater (see Annex A).
- LH-TES: a simplified adiabatic model of the latent heat thermal energy storage system is implemented to calculate the energy stored and the state of charge of the LH-TES tank.
- SH-TES: the sensible heat thermal energy storage system is simulated using two adiabatic variable volume storage tanks containing water at two different temperature levels.

Other TRNSYS types that are excluded from the previous classification are:

- INPUTS: *POWER FILE*, *SOURCE* and *SINK* are values to be changed by the user in order to adapt the model to the corresponding case study.

- INTERNAL CALCULATIONS: [TES>SH-TES] *TANKS PARAMETERS*, *T_LTWT OPTIONS A or B* and *ORC MAP SELECTION* are implemented to calculate parameters internally required in the model.

The functioning and interaction of all these components will be explained in detail in the following sections. As a general idea, the "INPUTS" define the performance of the equipment (HT-HP and ORC) which determines the state of charge of the TES system. The "CONTROL" system is responsible for controlling the amount of power provided to the HT-HP or produced by the ORC and stopping the system or expelling excess energy.

## 3.1 Classification of variables of the TRNSYS CHEST model

In order to design the model in TRNSYS, the CHEST system was implemented previously in EES giving detailed information about every parameter of the cycle. In order to structure this information and decide which of these variables could be implemented in TRNSYS and which ones will be given by the EES model, an analysis of all of them was carried out.

To obtain the independent variables that will be modified in TRNSYS, a classification of all the parameters of the system has been done. The considered variables (Figure 10) are:

- Melting temperature $T_{melt}$ of the PCM in the latent heat storage.
- Compressor efficiency.
- Efficiencies of expander and pump in ORC.
- Electrical power input/output for compressor, expander and pumps.
- Secondary fluid (source) inlet temperature and temperature difference of the HT-HP's evaporator.
- Secondary fluid (sink) inlet temperature and temperature difference of the ORC's condenser.
- Superheating in HT-HP evaporator and ORC's LH-TES.
- Pinch point ($\Delta T_{pinch}$) in heat exchangers.
- Temperatures of low-temperature water tank ($T_{LTWT}$) and high-temperature water tank ($T_{HTWT}$).
- Secondary fluid mass flow rates in subcooler, preheater, HT-HP's evaporator, and ORC's condenser.
- Refrigerant mass flow rates in HP and ORC.
- Pressure drop in heat exchangers.
- Heat capacities of heat exchangers.

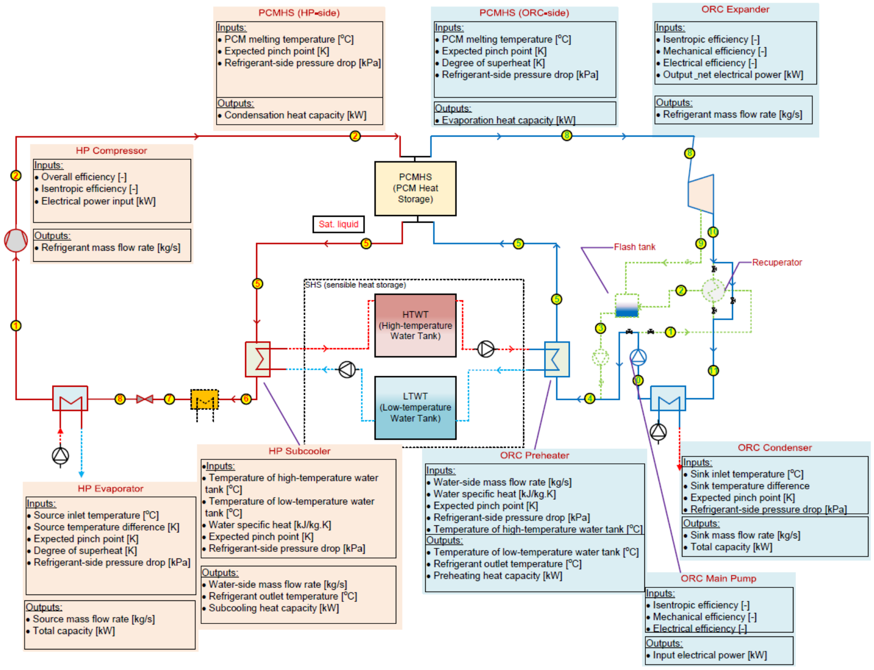


*Figure 10: Variables of EES-CHEST system.*

The variables have been classified in three different categories, as follows:

- Fixed variables: Their values have previously been predefined in the EES-CHEST model, they are constant in the entire simulation and cannot be changed in the TRNSYS-CHEST model. To change them, new performance maps would have to be generated. These variables are:
  - Efficiencies of compressor, the expander and pumps.
  - Pinch points and pressure drop in heat exchangers
    Superheat values inside the HT-HP's evaporator and ORC's LH-TES
- Independent variables: Variables that determine the dynamic performance of the system and which are inputs for the EES performance maps. They can be modified by the user or, in the case of the temperatures of the tanks, depend on the initial state of the system and its evolution in the TRNSYS-CHEST model:
  - Input electrical power for the HT-HP: $\boldsymbol{P_{input\_HP}}$
  - Water-side (source) Temperatures difference and inlet temperature for the HT-HP's evaporator: $\boldsymbol{T_{w\_inlet\_evap}}$ and $\boldsymbol{\Delta T_{w\_evap}}$
  - Net output power from the ORC: $\boldsymbol{P_{output\_ORC}}$
  - Temperatures of the condenser of the ORC: $\boldsymbol{T_{w\_inlet\_cond}}$ and $\boldsymbol{\Delta T_{w\_cond}}$
  - Optimum temperatures of the low temperature water tank and high temperature water tank: $\boldsymbol{T_{LTWT}}$ and $\boldsymbol{T_{HTWT}}$
- Dependent: Obtained as a function of the other variables:
  - Mass flow rate of water.
  - Heat capacities of the heat exchangers

The values of the fixed variables are given in Figure 11. The independent variables are marked in blue and; the values of the fixed variables are written in red; and the dependent variables are written in black:

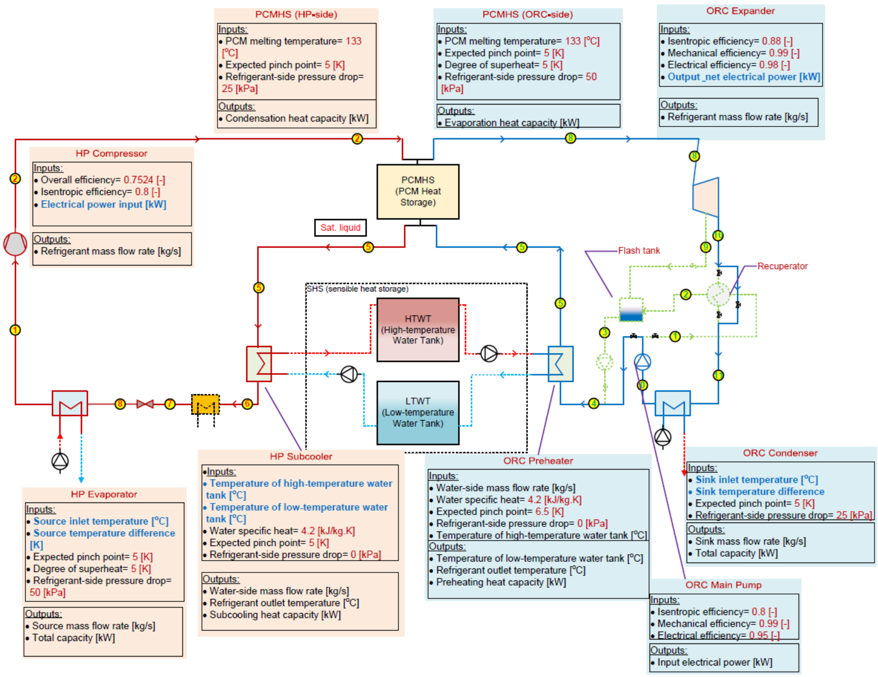


*Figure 11: Classification of variables of the CHEST system.*

Following this decision, there are in total five independent variables per equipment:

- HT-HP: $P_{input\_HP}$, $T_{w\_inlet\_evap}$, $\Delta T_{w\_evap}$, $T_{LTWT}$ and $T_{HTWT}$
- ORC: $P_{output\_ORC}$, $T_{w\_inlet\_cond}$, $\Delta T_{w\_cond}$, $T_{LTWT}$ and $T_{HTWT}$

## 3.2 Inputs to the TRNSYS-CHEST model

Once selected, the independent variables of the system can easily be changed, along with other basic parameters (see Annex A) such as sizing the equipment and TES system, in order to adapt the simulation to the corresponding case study. These inputs can be found either in external data readers (Type 9c) or as fixed values in *CONTROL CARDS*; and are related with the power generated or demanded, with the sizing of equipment and TES tanks or working temperatures of the system.

## 3.3 Performance maps

In order to generate the performance maps models for the HT-HP and the ORC the best option which was found was to model them independently in EES and generate the corresponding performance maps. Such maps can be integrated in TRNSYS by using linear interpolation types. The main drawback of this choice is that maps are created for one specific fluid and certain fixed parameters. So, for any change in refrigerant or parameters, new individual maps will have to be created. For the model of this report, Butene has been chosen as the heat transfer fluid for both HT-HP and ORC, see annex B for more information.

To introduce the maps in TRNSYS, Type 42 is used. This type allows for integration of maps that accept up to three independent variables as inputs with a maximum of five different values for each one; and up to five dependent variables as outputs. To calculate the outputs, it interpolates linearly within the values of the range.

Thus, the maximum number of points per map is $5^3$= 125.

As explained earlier, the classification of variables in Section 3.1 leads to five independent variables per equipment:

- HT-HP: $P_{input\_HP}$, $T_{w\_inlet\_evap}$, $\Delta T_{w\_evap}$, $T_{LTWT}$ and $T_{HTWT}$
- ORC: $P_{output\_ORC}$, $T_{w\_inlet\_cond}$, $\Delta T_{w\_cond}$, $T_{LTWT}$ and $T_{HTWT}$

To reduce the number of independent variables of the maps, the HT-HP and ORC performance maps were done for an electrical nominal power input/net of 1 MWel. Subsequently, sizing and scale factors were applied in the TRNSYS-CHEST model. Thus, the variables considered to do the maps are:

- HT-HP: $T_{w\_inlet\_evap}$, $\Delta T_{w\_evap}$, $T_{LTWT}$ and $T_{HTWT}$
- ORC: $T_{w\_inlet\_cond}$, $\Delta T_{w\_cond}$, $T_{LTWT}$ and $T_{HTWT}$

While the temperatures in the evaporator and the condenser are values that can be introduced by the user, the tank temperatures are obtained either from the corresponding type in the TRNSYS-CHEST model in the case of the HT-HP or by the optimum outlet water temperature from the preheater, obtained under certain operation conditions, for the ORC.

The results from the EES-CHEST models show that the optimum value of $T_{HTWT}$ is always equal to the melting temperature of the PCM, in this case equal to 133°C. Thus, $T_{HTWT}$ has been eliminated as independent variable and is fixed to 133°C for the elaboration of the performance maps.

The way to proceed with $T_{LTWT}$ is different for the HT-HP and ORC map. While in the first case the value of $T_{LTWT}$ is given as a boundary condition by the actual temperature of the tank in each timestep, for the ORC $T_{LTWT}$ corresponds with the optimum outlet water temperature in the preheater, and three different options have been implemented to obtain its value ($\boldsymbol{T_{\_opt\_LTWT}}$):

- Option A: Optimum outlet water temperature in the preheater (T_opt_LTWT) is obtained from a correlation from the coupled model of the CHEST system. The TRNSYS-CHEST system is dynamic but this helps as a first control strategy.
- Option B: Optimum temperature can be optimized by the user in *CONTROL CARDS* (by means of the variable T_opt_LTWT_user_option_B)
- Option C: T_opt_LTWT is obtained as an output of the ORC performance map when fixing the condition of having saturated liquid at the outlet of the preheater. This option might be interesting to simulate laboratory conditions.

Based on this, the independent variables for each one of the maps are:

- HT-HP map: $T_{w\_inlet\_evap}$, $\Delta T_{w\_evap}$, $T_{LTWT}$
- ORC map for Option A and B: $T_{w\_inlet\_cond}$, $\Delta T_{w\_cond}$, and $T_{\_opt\_LTWT}$
- ORC map for Option C: $T_{w\_inlet\_cond}$ and $\Delta T_{w\_cond}$

The range of each variable has been selected to cover the six different operating modes of the CHEST system. In the case of $\Delta T_{w\_cond}$, it has a wider range than $\Delta T_{w\_evap}$ in order to allow the integration with the district heating system. Average values of the sink and source temperatures for each working mode (Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, Figure 8) of can be seen in Table 1:

*Table 1: Source and sink temperatures in the different working modes.*

| Variable | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 | Mode 6 |
|---|---|---|---|---|---|---|
| $T_{w\_inlet\_evap}$ | 80 | 80 | 100 | 100 | 60 | 40 |
| $T_{w\_inlet\_cond}$ | 40 | 10 | 40 | 10 | 60 | 60 |

One of the key features of the CHEST concept, which clearly makes a difference from other competing technologies, is the high flexibility that it offers, which allows to efficiently respond under different boundary conditions and needs. The CHEST concept integrated into Smart DH System offers a variety of operation modes that can be actively chosen. Depending on the current state of boundary conditions, it offers the possibility to convert more heat into power, or more power into heat (Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, Figure 8).

## 3.4 TRNSYS CHEST model control strategy

A control strategy for the model has been developed in order to check that the behaviour of the system is consistent. The following steps were followed:

1. Control of the power entering the HT-HP or to be produced by the ORC.
2. Control of the load conditions for both the HT-HP and ORC.
3. Control of the level of SH-TES and LH-TES tanks.
4. Control of temperatures of the SH-TES tanks for the correct functioning of the equipment.

These different variables are used to limit either the entering power that drives the HT-HP or ORC or the heat that is stored or removed from the tanks.

## 3.5 Power Control

The first check is to ensure that the HT-HP and ORC are not working during the same timestep, as that means that there is electricity production from renewable energy sources available to cover the demand, or at least part of it, so there is no need to use it to drive the HT-HP and store energy in the TES tanks. To do so, the power can be directly bypassed from one side to another, without using the storage system, by means of the variable **P_el_bypass_RES_MW**[1]**:**

$$\begin{aligned} P\_el\_bypass\_RES \\ &= (P\_el\_out\_RES > P\_el\_dem) * P\_el\_dem \\ &+ (P\_el\_out\_RES < P\_el\_dem) * P\_el\_out\_RES \\ &+ (P\_el\_out\_RES = P\_el\_dem) * P\_el\_dem \end{aligned} \quad (1)$$

According to equation (1), the bypassed power is equal to the lower value (P_el_out_RES or P_el_dem) at each timestep. Then, the surplus power available to drive the HT-HP or the deficit power, to be supplied by the ORC, is:

[1] In the following equations, expressions such as $(\text{P\_el\_dem} > \text{P\_el\_out\_RES})$ are employed. They actually are control variables which have a value of 1 if the condition written in brackets is true and 0 if it is false. In TRNSYS this is programmed using the commands GT (Greater Than), LT (Lower Than) or EQL (Equal).

$$\boldsymbol{P\_el\_surplus\_RES\_MW} = P\_el\_out\_RES - P\_el\_bypass\_RES \quad (2)$$

$$\boldsymbol{P\_el\_def\_pass\_dem\_MW} = P\_el\_dem - P\_el\_bypass\_RES \quad (3)$$

Once the surplus and the deficit power are defined, it should be taken into account that their values can be higher than the maximum that the equipment can work with. Thus, to ensure that the actual power, useful for HT-HP or that the ORC can supply does not exceed the maximum capacity, the following control variables have been defined:

$$\boldsymbol{SF\_P\_el\_in\_HP} = (P\_el\_surplus\_RES > P\_el\_in\_nom\_HP) \quad (4)$$

$$\boldsymbol{SF\_P\_el\_net\_ORC} = (P\_el\_def\_pass\_dem > P\_el\_net\_nom\_ORC) \quad (5)$$

These variables will be 0 if the power is lower than the size and 1 otherwise. The real usable power (estimated electrical power) will take values between zero and the size of the equipment:

$$\boldsymbol{P\_el\_in\_est\_HP\_MW} = P\_el\_surplus\_RES * (1 - SF\_P\_el\_in\_HP) + P\_el\_in\_nom\_HP * SF\_P\_el\_in\_HP \quad (6)$$

$$\boldsymbol{P\_el\_net\_est\_ORC\_MW} = P\_el\_def\_pass\_dem * (1 - SF\_P\_el\_net\_ORC) + P\_el\_net\_nom\_ORC * SF\_P\_el\_net\_ORC \quad (7)$$

These last two variables are the ones connected to the performance maps, since they can be employed to drive the HT-HP or the ORC at each timestep.

## 3.6 Control of the Load Conditions

As the performance maps are done for a size of the systems of 1 MWel working at full load, scale and size factors are applied in the case that the load or the size differs from this value.

In the maps, obtained in the EES model, the following values are obtained:

- P_q_sen_nom: sensible heat in MW
- P_q_lat_nom: latent heat in MW

In the TRNSYS-CHEST model these parameters are scaled according to the actual size of the equipment and its current load.

In the maps introduced in TRNSYS-CHEST model the parameters are introduced for a heat pump or an ORC of 1 MWe of nominal power working at full capacity. If the power is different from 1 MWe, these output parameters have to be sized and scaled. There are two different variables per system to pay attention to:

1. Maximum capacity of the HP or ORC (P_el_in_nom_HP_MW or P_el_net_nom_ORC_MW).
2. Power input/output at each timestep (P_el_in_est_HP_MW or P_el_net_est_ORC_MW). Actual estimated power provided to the HP or demanded to be supplied by the ORC in every timestep. In this case, there are two different situations per component:

- <u>HEAT PUMP</u>
    a. P_el_in_est_HP = P_el_in_nom_HP → HP is working at full load
    b. P_el_in_est_HP < P_el_in_nom_HP →HP is working at partial load, scale factor (**F_q_capacity_PLR_HP**) is employed.

- <u>ORGANIC RANKINE CYCLE:</u> This is analogous to the heat pump.
    a. P_el_net_est_ORC = P_el_net_nom_ORC_MW → ORC is working at full load
    b. P_el_net_est_ORC < P_el_net_nom_ORC_MW →ORC is working at partial load, scale factor (**F_capacity_PLR_ORC**) is used.

## 3.7 Heat Pump Scaling and Sizing Factors

References show that, for heat pumps with variable speed in the compressor, there is an increase in the COP when working at a partial load (between 30-50%). This is due to the fact that the mass flow rate also decreases, leading to a reduction in the temperature difference in the evaporator and condenser, which lowers the compressor ratio [2][3].

Figure 12 shows several examples from literature illustrating this behaviour:

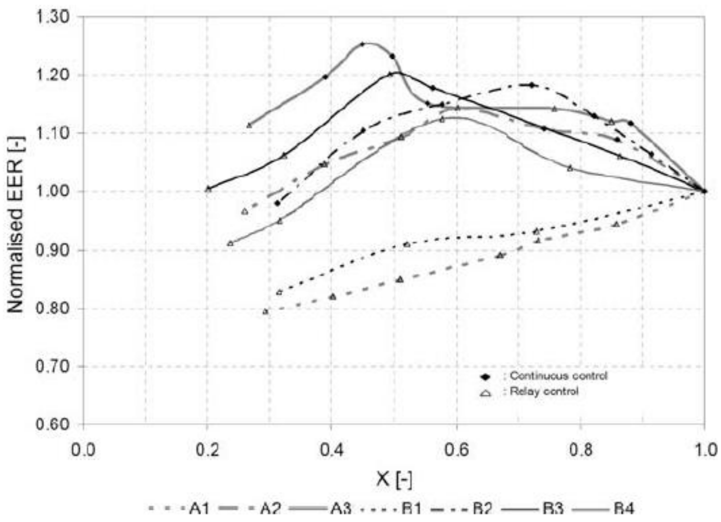


*Figure 12: Normalized EER vs Load of compressor*[2].

In Figure 12 the normalized Energy Efficiency Ratio (EER) is plotted as a function of the load of the compressor for different configurations: A1 and B1 represent cases without an inverter; A2 and B2 are single inverter compressors; and A3, B3 and B4 are cases with two compressors in tandem configuration, one of them driven by an inverter. As can be seen, in cases with an inverter there is an improvement of the efficiency when working at partial load, reaching their maximum value at 50% of the load.

In published literature [3], the improvement of using an inverter to operate at partial load instead of an ON-OFF controller is highlighted, as it allows to reduce the temperature difference in the condenser and evaporator, decreasing the compression ratio and improving the efficiency for loads around 50%.

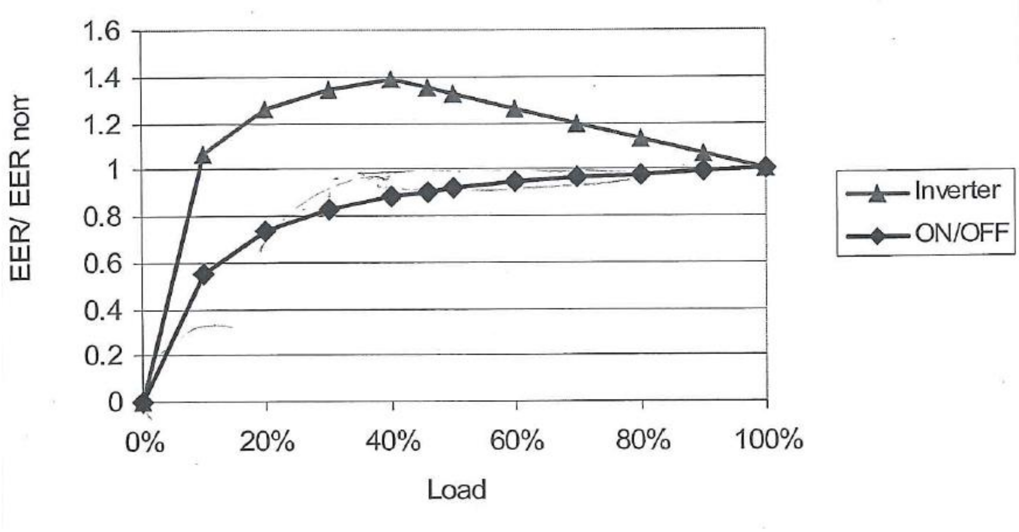


*Figure 13*: *EER/EER_nom in inverter and ON/OFF compressors*[3].

Experimental research carried out by CETITAT shows the same behaviour for different air temperatures [4] (Figure 14):

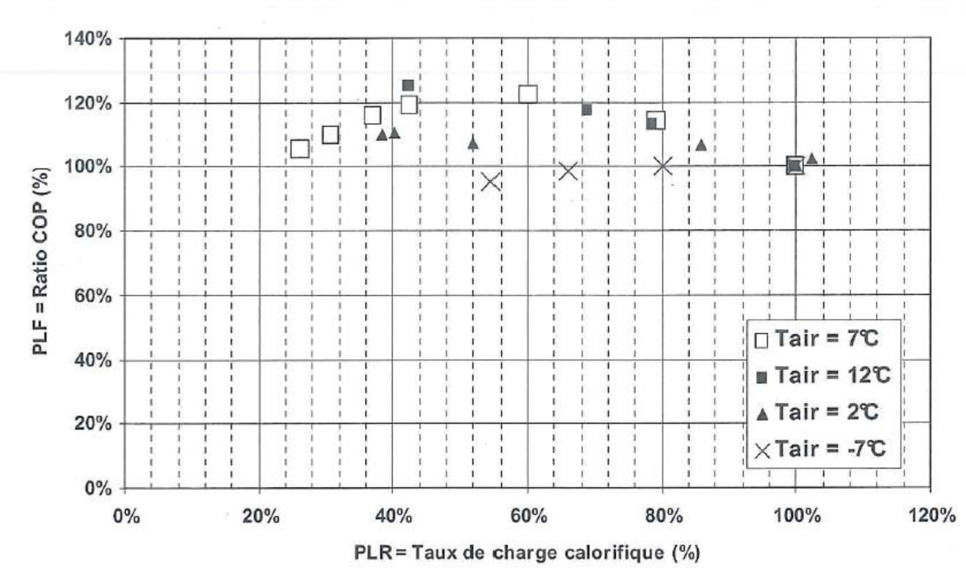


*Figure 14*: *PLF vs PLR* [4].

The same pattern is presented in other compressors that can be found in the market. As an example, the performance of the model Turbocor TT500 is shown in the illustration of Figure 15. [5].

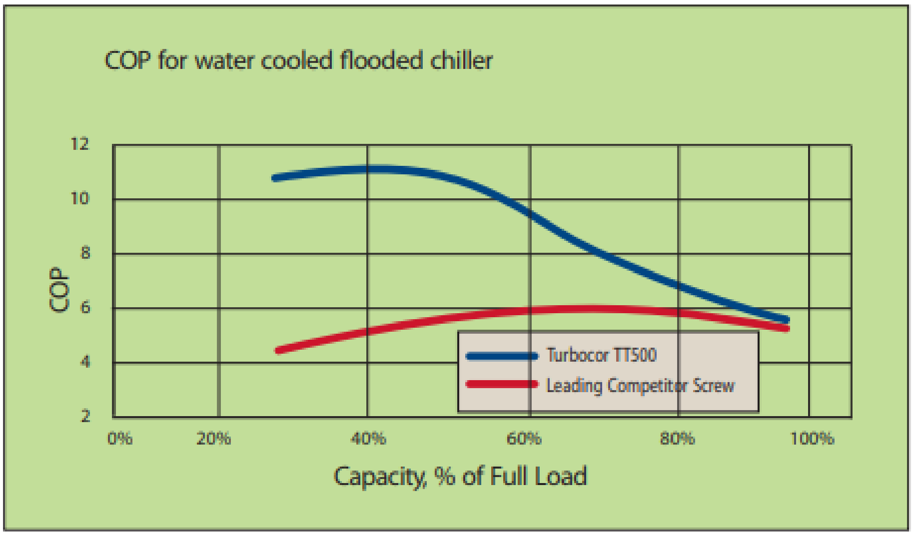


*Figure 15: COP vs capacity in TURBOCOR compressors* [5].

The relationship between the fractional capacity and COP was also studied in [6] for three different motors (b=basic, m=modern and n=new design). The results indicate an increase in the COP when the load is lower than 100%.

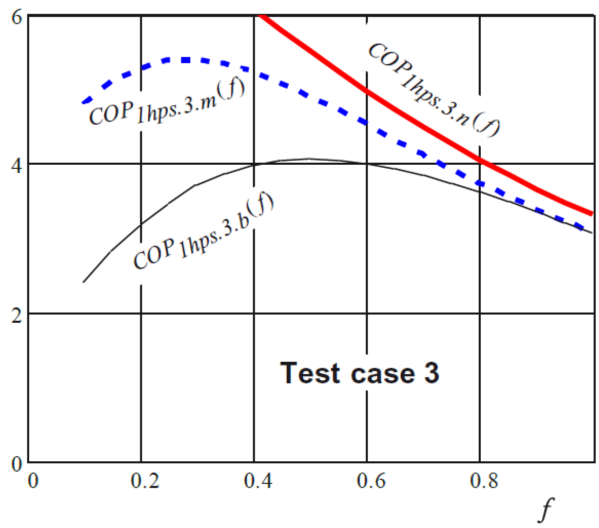


*Figure 16: COP vs fractional capacity* [6].

Figure 16 resumes the values of COP for different loads. As can be observed in case 3 (adapted flow) for a modern motor, the maximum COP is reached for the minimum load:

Table 2: COP at different load fractions [6].

| Alternative | COP | $f = 1.0$ | $f = 0.5$ | $f = 0.2$ |
|---|---|---|---|---|
| 1. Constant evaporating and condensing temperature. | $COP_{1hps.1.b}$ | 3.1 | 2.4 | 1.4 |
| | $COP_{1hps.1.m}$ | 3.1 | 2.8 | 2.2 |
| | $COP_{1hps.1.n}$ | 3.3 | 3.2 | 2.8 |
| 2. Constant flow rates, constant fan powers. Decreasing temperature lift. | $COP_{1hps.2.b}$ | 3.1 | 3.5 | 2.8 |
| | $COP_{1hps.2.m}$ | 3.1 | 4.1 | 4.0 |
| | $COP_{1hps.2.n}$ | 3.3 | 4.5 | 4.7 |
| 3. Adapted flow rates, decreasing fan powers. Decreasing temperature lift. | $COP_{1hps.3.b}$ | 3.1 | 4.1 | 3.2 |
| | $COP_{1hps.3.m}$ | 3.1 | 4.9 | 5.3 |
| | $COP_{1hps.3.n}$ | 3.3 | 5.5 | 7.1 |

## 3.8 Heat Pump Scale Factors in the TRNSYS-CHEST Model

The scale factors in the case that the HT-HP is working at partial load have been calculated following the pattern illustrated above. To do this, values from case 3 (Figure 16 and Table 2) have been used:

Table 3: Values of COP and ratios between actual and nominal COP at different Partial Load Ratios (PLR).

| PLR | 1 | 0.8 | 0.6 | 0.5 | 0.3 | 0.2 | 0.1 |
|---|---|---|---|---|---|---|---|
| COP | 3.1 | 3.6 | 4.5 | 4.9 | 5.5 | 5.3 | 4.9 |
| COP/COP_nom | 1.000 | 1.161 | 1.452 | 1.581 | 1.774 | 1.710 | 1.581 |

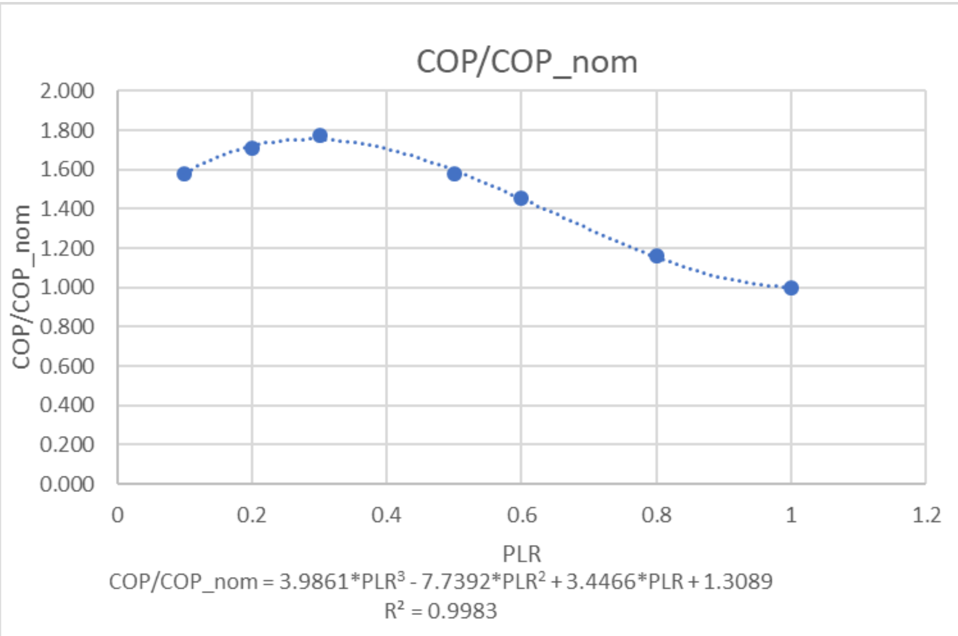


Figure 17: Ratio between actual and nominal COP at different PLR values.

In TRNSYS-CHEST model, the Partial Load Ratio (**F_PLR_HP**) of the HT-HP is calculated as follows (8):

$$F\_PLR\_HP = \frac{P\_el\_in\_est\_HP}{P\_el\_in\_nom\_HP} \quad (8)$$

The actual COP of HT-HP (**COP_HP**) is obtained as a function of the PLR and the COP of the HT-HP working at full load (9):

$$\begin{aligned} COP\_HP &= COP\_nom\_HP * \left[\frac{COP}{COP\_nom\_HP}(PLR)\right] \\ &= COP\_nom\_HP * (3.9861 * F\_PLR\_HP^3 - 7.7392 \\ &* F\_PLR\_HP^2 + 3.4466 * F\_PLR\_HP + 1.3089) \end{aligned} \quad (9)$$

Having the actual COP, the sum of sensible and latent heat is obtained for actual (10) and nominal conditions (11):

$$\boldsymbol{P\_q\_tot\_est\_HP\_MW} = COP\_HP * P\_el\_in\_est\_HP \quad (10)$$

$$\boldsymbol{P\_q\_tot\_nom\_HP\_MW} = COP\_nom\_HP * P\_el\_in\_nom\_HP \quad (11)$$

The scale factor F_q_capacity_PLR_HP is calculated as (12):

$$F\_q\_capacity\_PLR\_HP = \frac{P\_q\_tot\_est\_HP\_MW}{P\_q\_tot\_nom\_HP\_MW} \quad (12)$$

This is used to scale the other outputs of the performance map.

## 3.9 Heat pump sizing factor in the chest model: [HT-HP] SCALE & SIZE

In case the nominal input power of the equipment differs from 1 MWel, a sizing factor (**F_size_nom_HP**) is applied (13). As a first approach, this sizing factor will be linearly proportional to the nominal input power of 1 MW.

$$F\_size\_nom\_HP = \frac{P\_el\_in\_nom\_HP}{1\ MW} \quad (13)$$

Thus, considering all the parameters mentioned before, the estimated thermal capacities are (14)(15):

$$\begin{aligned} &\boldsymbol{P\_q\_lat\_est\_HP\_MW} \\ &\quad = F\_size\_nom\_HP * F\_q\_capacity\_PLR\_HP \\ &\quad * P\_q\_lat\_nom\_HP \end{aligned} \quad (14)$$

$$\begin{aligned} &\boldsymbol{P\_q\_sen\_est\_HP\_MW} \\ &\quad = F\_size\_nom\_HP * F\_q\_capacity\_PLR\_HP \\ &\quad * P\_q\_sen\_nom\_HP \end{aligned} \quad (15)$$

Also, the actual evaporator capacity, considering the mechanical and electrical compressor efficiencies (eta_mech_comp_HP and eta_el_comp_HP) introduced in EES, is calculated in *[HT-HP] SCALE & SIZE* (16), taking into account the scale and sizing factors explained in this section and also TES control factors that will be explained in section 3.11:

$$\boldsymbol{P\_q\_evap\_HP\_MW} = (P\_q\_sen\_est\_HP + P\_q\_lat\_est\_HP - (P\_el\_in\_est\_HP * eta\_mech\_comp\_HP * eta\_el\_comp\_HP)) * F\_ctrl\_char\_TES \quad (16)$$

## 3.10 Organic Rankine Cycle Scaling and Sizing Factors: [ORC] SCALE & SIZE

For the ORC, proportional sizing and scale factors are employed (17)(18)(19)(20):

$$\boldsymbol{F\_capacity\_PLR\_ORC} = \frac{P\_el\_net\_est\_ORC\_MW}{P\_el\_net\_nom\_ORC} \quad (17)$$

$$\boldsymbol{F\_size\_nom\_ORC} = \frac{P\_el\_net\_nom\_ORC}{1\ MW} \quad (18)$$

$$\boldsymbol{P\_q\_lat\_est\_ORC\_MW} = F\_size\_nom\_ORC * F\_capacity\_PLR\_ORC * P\_q\_lat\_nom\_ORC \quad (19)$$

$$\boldsymbol{P\_q\_sen\_est\_ORC\_MW} = F\_size\_nom\_ORC * F\_capacity\_PLR\_ORC * P\_q\_sen\_nom\_ORC \quad (20)$$

## 3.11 Thermal Energy Storage: [TES] CONTROL.

Estimated latent and sensible heats for both the HT-HP and ORC are previously obtained from the scaling and sizing factors mentioned above. However, it is necessary to check that the amount of heat available in a timestep fits in the thermal storage system, and also, if the heat demanded by the ORC can be provided by the tanks. Otherwise, the system has to be stopped.

In the case of the latent heat storage, the control is done by ensuring that the energy entering the tank is less than the remaining energy in the tank during the charging (*char*) process (21); and that the energy leaving the tank is less than the total energy stored in it in the discharge (*dchar*) (22).

$$\boldsymbol{F\_char\_LHS} = (P\_q\_lat\_est\_HP * step) < (E\_q\_max\_LHS\_MWh - E\_q\_lat\_TES\_MWh) \quad (21)$$

$$\boldsymbol{F\_dchar\_LHS} = (P\_q\_lat\_est\_ORC * step) < E\_q\_lat\_TES\_MWh \quad (22)$$

The variable E_q_lat_TES_MWh corresponds to the energy stored in the LH-TES tank in each timestep.

To control the sensible heat storage, the level of water of the tanks is checked every timestep (*step*)(23)(24). Therefore, in the charge process the cold tank has to have enough available water to provide the demanded mass flow rate during the specified interval of time; and for the discharge, the hot tank has to be full enough to cover the mass flow demand [2].

$$\boldsymbol{F\_char\_V\_SHS} = (V\_w\_LTWT\_SHS - V\_w\_min\_SHS) > \frac{m\_est\_subc\_HP * step}{Rho\_w} \tag{23}$$

$$\boldsymbol{F\_dchar\_V\_SHS} = (V\_w\_HTWT\_SHS - V\_w\_min\_SHS) > \frac{m\_est\_preh\_ORC * step}{Rho\_w} \tag{24}$$

The mass flow rates used for the calculation of these control variables have been obtained using the sensible scaled heats calculated before (P_q_sen_est_HP and P_q_sen_est_ORC), the temperatures of SH-TES tanks (**T_w_LTWT_SHS_C** and **T_w_HTWT_SHS_C**) and the optimum outlet temperatures from the subcooler and the preheater (**T_w_out_subc_HP_C** and **T_w_out_preh_ORC_C**)(25)(26):

$$\boldsymbol{m\_est\_subc\_HP\_kg\_s} = \frac{P\_q\_sen\_est\_HP}{Cp\_w * (T\_w\_out\_subc\_HP - T\_w\_LTWT\_SHS)} \tag{25}$$

$$\boldsymbol{m\_est\_preh\_ORC\_kg\_s} = \frac{P\_q\_sen\_est\_ORC}{Cp\_w * (T\_w\_HTWT\_SHS - T\_w\_out\_preh\_ORC)} \tag{26}$$

In the charge process the value of T_w_out_subc_HP is always equal to 133 °C and, for T_w_out_preh_ORC, its value will depend on the option (A, B or C) selected.

As E_q_lat_TES_MWh, V_w_LTWT_SH-TES and V_w_HTWT_SH-TES change along each timestep, the control variables cannot use their instantaneous value of them but the initial one of the timestep. To achieve that, Type150 (Delayed Inputs Controller) has been used to save the last value of the previous time step during the next one. This approach avoids convergence problems during the simulation.

## 3.12 Control of Temperatures in the SH-TES Tanks

As the ORC performance map is done for a T_w_HTWT_SH-TES of 133 °C, the temperature of the hot tank cannot be below this value during the discharge process. Otherwise the output obtained in the ORC Map would be incorrect. Hereby, the following control has been made (27):

$$\boldsymbol{SF\_T\_dchar\_HTWT} = (T\_w\_HTWT\_SHS > 130) \tag{27}$$

## 3.13 Outputs Obtained from Control Variables

The control strategy allows the functioning of the HT-HP as long as one of the storage systems (LH-TES or SH-TES) is not full yet and is able to store more energy, expelling extra sensible or

[2] V_w_LTWT_SH-TES-V_w_min_SH-TES corresponds with the useful amount of water contained in the LTWT, that can be sent to the HTWT

latent heat when one system is filled before the other. The ORC will also stop t when one of the storage systems is empty.

Depending on the temperature conditions in the source and the sink, an imbalance may appear between the ratios of sensible and latent heat for charge and discharge, meaning that, if the system is stopped when one of the storage tanks is full or empty, after a certain number of cycles, one of the TES tanks may be full and the other empty[3]. If this happens, the CHEST system would be blocked, as it would not be capable of charging or discharging energy. This is the reason why the control strategy allows the charging of the CHEST system until both the LH-TES and SH-TES are full and, in case one system charges before the other, an extra heat exchanger is activated to expel the excess heat.

The latent heat entering or leaving the LH-TES system is defined as (28):

$$\boldsymbol{P\_q\_lat\_TES\_MW} = P\_q\_lat\_est\_HP * F\_char\_LHS - P\_q\_lat\_est\_ORC * F\_dchar\_V\_SHS * F\_dchar\_LHS * SF\_T\_dchar\_HTWT \quad (28)$$

The sensible heat charged or discharged is calculated as follows (29)(30):

$$\boldsymbol{P\_q\_sen\_char\_TES\_MW} = P\_q\_sen\_est\_HP * F\_char\_V\_SHS \quad (29)$$

$$\boldsymbol{P\_q\_sen\_dchar\_TES\_MW} = P\_q\_sen\_est\_ORC * F\_dchar\_V\_SHS * F\_dchar\_LHS * SF\_T\_dchar\_HTWT \quad (30)$$

The excess (latent and sensible) heats that may be expelled from the system are calculated as (31)(32):

$$\boldsymbol{P\_q\_lat\_excess\_HP\_MW} = P\_q\_lat\_est\_HP * F\_char\_V\_SHS * (1 - F\_char\_LHS) \quad (31)$$

$$\boldsymbol{P\_q\_sen\_excess\_HP\_MW} = P\_q\_sen\_est\_HP * F\_char\_LHS * (1 - F\_char\_V\_SHS) \quad (32)$$

Finally, as the power employed to drive the different components of the CHEST system is not limited by the volume and temperature control variables, a calculation of the actual useful power is done in order to evaluate the performance of the system (33)(34).

$$\boldsymbol{P\_el\_in\_HP\_MW} = P\_el\_in\_est\_HP * F\_ctrl\_char\_TES \quad (33)$$

$$\boldsymbol{P\_el\_net\_ORC} = P\_el\_net\_est\_ORC * F\_dchar\_V\_SHS * F\_dchar\_LHS * SF\_T\_dchar\_HTWT \quad (34)$$

To control the input power to the HT-HP, the variable F_ctrl_char_TES is used (35):

$$\boldsymbol{F\_ctrl\_char\_TES} = (F\_char\_LHS + F\_char\_V\_SHS) > 0 \quad (35)$$

[3] The systems may not be completely full or empty, but they do not have sufficient capacity to charge or discharge during the next timestep.

This variable is 1 when at least one of the storage systems can be charged and 0 if both are full.

## 3.14 Outputs from the TRNSYS-CHEST model

The results obtained in the TRNSYS model of the CHEST system are analysed by means of plots and excel files that are obtained at the end of the simulation.

Six plots are made to represent the state of the system:

- POWER: in this first plot a comparison among the different input and output power is made. Values from the input file are plotted and compared to the bypassed power and the actual power used or provided by the CHEST system. The variables represented are (Table 4):

*Table 4: Variables plotted in POWER.*

| Variable name | Units |
|---|---|
| **P_el_out_RES** | MW |
| **P_el_dem** | MW |
| **P_el_bypass_RES** | MW |
| **P_el_in_est_HP** | MW |
| **P_el_in_HP** | MW |
| **P_el_net_est_ORC** | MW |
| **P_el_net_ORC** | MW |

- TEMPERATURES: The evolution of the tank temperatures is presented along with the PCM melting temperature and sink and source temperatures chosen according to the working mode (Table 5).

*Table 5: Variables plotted in TEMPERATURES.*

| Variable name | Units |
|---|---|
| **T_w_in_evaporator** | °C |
| **T_w_in_condenser** | °C |
| **T_w_HTWT** | °C |
| **T_w_LTWT** | °C |
| **T_melt_PCM** | °C |

- STORAGE: Variables of state of Thermal Storage System (TES) are plotted for both sensible and latent tanks (Table 6).

*Table 6: Variables plotted in STORAGE.*

| Variable name | Units |
|---|---|
| **P_q_lat_TES** | MW |
| **P_q_sen_TES** | MW |
| **F_LoC_LH-TES** | - |
| **F_LoC_SH-TES** | - |

- LH-TES: the energy stored in the tank in compared to the power injected or rejected from it (Table 7).

*Table 7: Variables plotted in the LH-TES.*

| Variable name | Units |
|---|---|
| **P_q_lat_TES** | MW |
| **E_q_lat_TES** | MWh |

- SH-TES: Charge and discharge mass flow rates are presented with the evolution of the water volume contained in the SH-TES tanks (Table 8).

*Table 8: Variables plotted in the SH-TES.*

| Variable name | Units |
|---|---|
| **m_w_subc_HP_kg_h** | kg/h |
| **m_w_preh_ORC_kg_h** | kg/h |
| **V_w_HTWT_SH-TES** | $m^3$ |
| **V_w_LTWT_SH-TES** | $m^3$ |

- EXCESS: Sensible and latent excess power is plotted with the LoC of each system (Table 9).

*Table 9: Variables plotted in EXCESS.*

| Variable name | Units |
|---|---|
| **P_q_lat_excess_HP** | MW |
| **P_q_sen_excess_HP** | MW |
| **F_LoC_LH-TES** | - |
| **F_LoC_SH-TES** | - |

Additionally, an excel file with an annual balance is obtained. Inside, the output energy from RES generation is compared to the energy charged in the system, classifying the energy excess that cannot be used due to HT-HP nominal power restrictions (E_el_ex_RES_size_HP) or due to the sizing of the TES systems (E_el_ex_RES_size_TES). The same process is done for the ORC, comparing the demanded energy output with the net electrical energy produced by the ORC and the demand of energy not covered by the system (E_el_def_tot_dem). Finally, the sensible and latent energy excess from the HT-HP are also represented. With this information, the roundtrip efficiency is calculated. The complete list of variables is (Table 10):

*Table 10: Variables obtained in the GLOBAL PERFORMANCE excel file.*

| Variable name | Units |
|---|---|
| **E_el_out_RES** | MWh |
| **E_el_dem** | MWh |
| **E_el_bypass_RES** | MWh |
| **E_el_surplus_RES** | MWh |
| **E_el_def_dem_bypass** | MWh |
| **E_el_in_HP** | MWh |
| **E_el_ex_RES_size_HP** | MWh |
| **E_el_ex_RES_size_TES** | MWh |
| **E_el_net_ORC** | MWh |
| **E_el_def_tot_dem** | MWh |
| **Eta_roundtrip_CHEST** | MWh |
| **E_q_sen_excess_HP** | MWh |
| **E_q_lat_excess_HP** | MWh |

Thus, the RES energy production and energy demand are split in the components showed below (36)(37):

$$E\_el\_out\_RES = E\_el\_bypass\_RES + E\_el\_in\_HP + E\_el\_ex\_RES\_size\_HP + E\_el\_ex\_RES\_size\_TES \quad (36)$$

$$E\_el\_dem = E\_el\_bypass\_RES + E\_el\_net\_ORC + E\_el\_def\_tot\_dem \quad (37)$$

In order to compare the different results obtained from the different case studies, these outputs will be compared; the ratio between the electrical energy consumed by HP and the total amount of electrical energy output from the RES (r_E_el_in_HPtoRES) ; the ratio between the electrical energy bypassed and the total amount of electrical energy output from the RES (r_E_el_BYPASStoRES) ;the ratio between the excess electrical energy from RES that cannot be used due to HP's size restriction and the total amount of electrical energy output from the RES (r_E_el_ex_HPtoRES); the ratio between the excess electrical energy from RES that cannot be used due to TES's size restrictions and the total amount of electrical energy output from the RES (r_E_el_ex_TEStoRES); the ratio between the net electrical energy output by ORC and the total amount of electrical energy demanded (r_E_el_net_ORCtoDEM); the ratio between the electrical energy bypassed and the total amount of electrical energy demanded (r_E_el_BYPASStoDEM) and the ratio between the total deficit in the demand-side and the total amount of electrical energy demanded (r_ E_el_def_TOTtoDEM) (Table 11).

*Table 11: Variables obtained in the Ratios excel file.*

| Variable name | Units |
|---|---|
| **r_E_el_in_HPtoRES** | - |
| **r_E_el_BYPASStoRES** | - |
| **r_E_el_ex_HPtoRES** | - |
| **r_E_el_ex_TEStoRES** | - |
| **r_E_el_net_ORCtoDEM** | - |
| **r_E_el_BYPASStoDEM** | - |
| **r_ E_el_def_TOTtoDEM** | - |

# 4 Preliminary assessment for CHEST components under different boundary conditions and needs

In order to validate the CHEST concept under different boundary conditions, and for acquiring a better knowledge of the requirements to be considered for the different CHEST components, the TRNSYS simulation tool is going to be applied to each one of the six operation modes considered for the CHEST system.

Furthermore, three different scenarios will be defined in order to cover the needs depending on energy availability and demand requirements over the year:

- Summer season
- Winter season
- Transitional period.

These scenarios are actually profiles that will represent the energy availability and demand (both, electrical and thermal) over these periods.

## 4.1 Energy availability and demand requirements

The three different scenarios defined within this analysis (Summer, Winter and Transitional period) represent both, the available energy and the energy demand for each period.

For the available energy, electrical energy provided by wind farms and photovoltaic systems are considered, as well as the thermal heat provided by solar heating systems. According to the energy demand, the domestic heat demand, the consumption of electrical energy and the process of charging the seasonal thermal energy storage are considered. The structure for each scenario, as well as the operation strategy that each scenario will intend to represent, can be seen in Table 12.

*Table 12: Available energy and demand for different seasons.*

| Season | Available energy (typical structure)<br>PV<br>Solar heat<br>Wind | Demand (typical structure)<br>Domestic heat<br>Charging seasonal storage<br>Electric energy | Operation strategy |
|---|---|---|---|
| Summer | | | Storage is mainly used for storage of electric energy |
| Winter | | | Storage delivers both heat and electricity<br>Heat pump may be used to provide domestic heat |
| Transitional period | | | Storage delivers both heat and electricity, depending on demand<br>Heat pump may be used to (re) charge seasonal storage |

## 4.2 Simulation results

For each scenario, summer, winter and transitional period **a design month profile** has been defined in order to carry out the first approach of CHEST components sizing. (see Annex C). Each working mode may be suitable for one or two seasons depending on each boundary conditions. However, the outputs that have been compared are the same for all the working modes and have been described in section 3, Table 5, Table 6, Table 10 and Table 11.

## 4.3 Mode 1 Results

Working mode 1 may represent the operation mode of the CHEST system in transitional periods or winter season when the DH needs heat production as well as electricity. The CHEST system will consume around 1MWel during charging, and it is expected it can deliver around 0.66MWel while discharging; assuming 80ºC as evaporation inlet temperature and 40ºC as condensation inlet temperature.

Table 13 shows the different case studies that have been defined for operation mode 1. In these cases, transitional scenario and a ratio of 1.2 between the total amount of electrical energy provided by the RES and the total amount of electrical energy demanded by the system have been selected as framework. The parameters that have been studied are: HP power, ORC power and sensible and latent storage capacities.

*Table 13: Case studies for working mode 1.*

| CASE | Season/Scenario | RESel/Dem.el | HP MW | ORC MW | SH-TES $m^3$ | LH-TES MWh |
|---|---|---|---|---|---|---|
| **1.1** | Transitional | 1.2 | 1 | 1 | 300 | 30 |
| **1.2** | Transitional | 1.2 | 1 | 2 | 300 | 30 |
| **1.3** | Transitional | 1.2 | 2 | 1 | 300 | 30 |
| **1.4** | Transitional | 1.2 | 2 | 2 | 300 | 30 |
| **1.5** | Transitional | 1.2 | 2 | 1 | 600 | 60 |
| **1.6** | Transitional | 1.2 | 2 | 1 | 300 | 60 |
| **1.7** | Transitional | 1.2 | 2 | 1 | 600 | 30 |

Figure 18 shows the results of running case studies 1.1, 1.2, 1.3 and 1.4, where it can be seen that, increasing the power capacity of the HP from 1 to 2 MW, will increase the round trip value from 0.49 to 0.61; decreasing the ratio between the excess electrical energy from the RES that cannot be used due to HP´s size restrictions and the total amount of electrical energy provided but the RES from 0.15 to 0.02. However, the ratio between the excess electrical energy that cannot be used due to TES´s size restrictions and the total the total amount of electrical energy provided but the RES increases significantly, from 0.24 to 0.4 (comparison between 1.1 and 1.3).

On the other hand, an increasement of ORC power from 1MW to 2MW, has no impact on these ratios (comparison between 1.1 and 1.2 or 1.3 and 1.4).

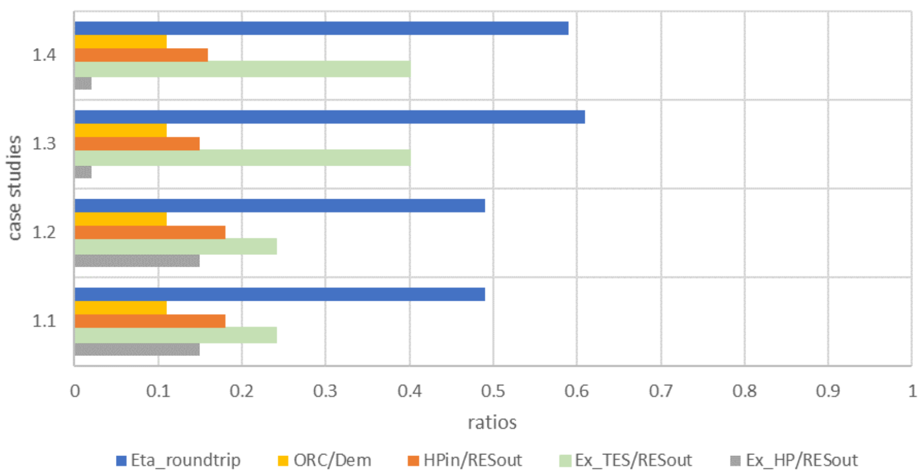


*Figure 18: Simulation results of 1.1, 1.2 1.3 and 1.4 case studies.*

Once case study 1.3 has been selected as the most promising case study, between 1.1-1.4, the storage volumes of the sensible and latent tanks have been doubled, case study 1.5.

Figure 19 shows a comparison between case studies 1.3 and 1.5, where it can be seen that the increasement of storage volume benefits the ratio between the net electrical energy output by ORC and the total amount of electrical energy demanded by the system, increasing this ratio from 0.11 to 0.17. However, the round trip efficiency decreases two points from 0.61 to 0.59. The main reason of this behaviour is that the heat pump works more hours, as it can be seen when comparing HPin/RESout ratio and, the temperature of the top of the PIT storage decreases (evaporation temperature) as seen in Figure 20. In case study 1.3, the thermal energy that the HP needs is 666MWh/month whereas, in case study 1.5, 1027MWh/month are required, which has a direct impact in the size of the PIT storage.

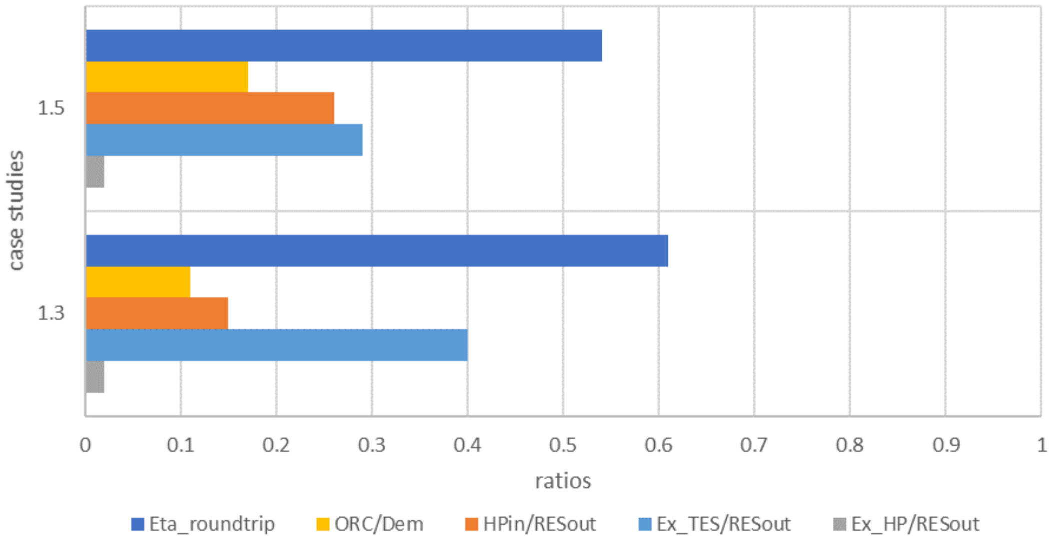


*Figure 19: Simulation results of case studies 1.3 and 1.5.*

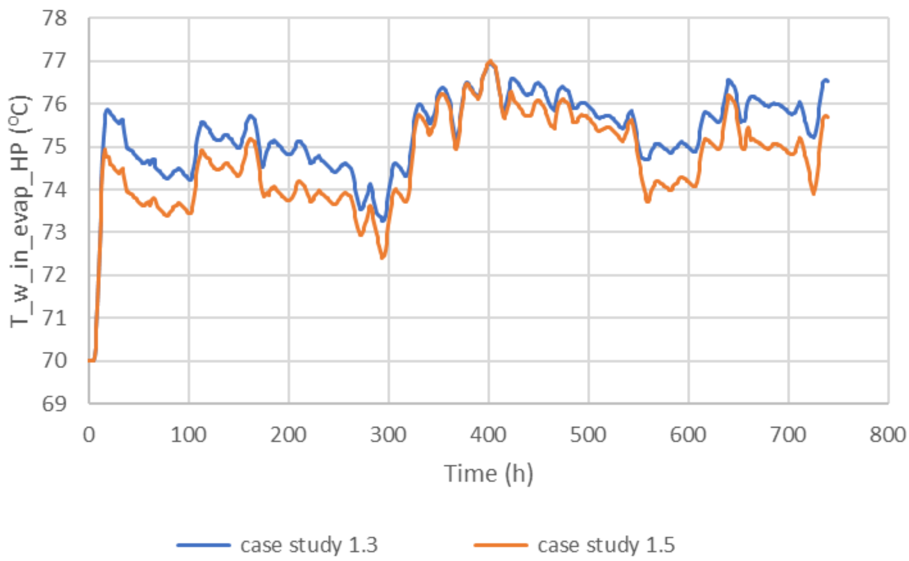


*Figure 20: HP evaporator water inlet temperature.*

In order to know the impact of the sensible and latent heat storage volumes, case studies 1.6 and 1.7 have been run. For case study 1.6, the volume of SH-TES has been maintained in 300m$^3$, whereas the maximum storage capacity of the LH-TES has been doubled to 60MWh. For case study 1.7, the SH-TES volume has been double to 600m$^3$ and, LH-TES maximum capacity maintained in 30MWh.

Figure 21 shows the results of case studies 1.3, 1.5, 1.6 and 1.7 where it can be seen that there is no benefit in increasing only one of each storage. In order to obtained better results, both storages have been increased, as it can be seen in the results of case study 1.5.

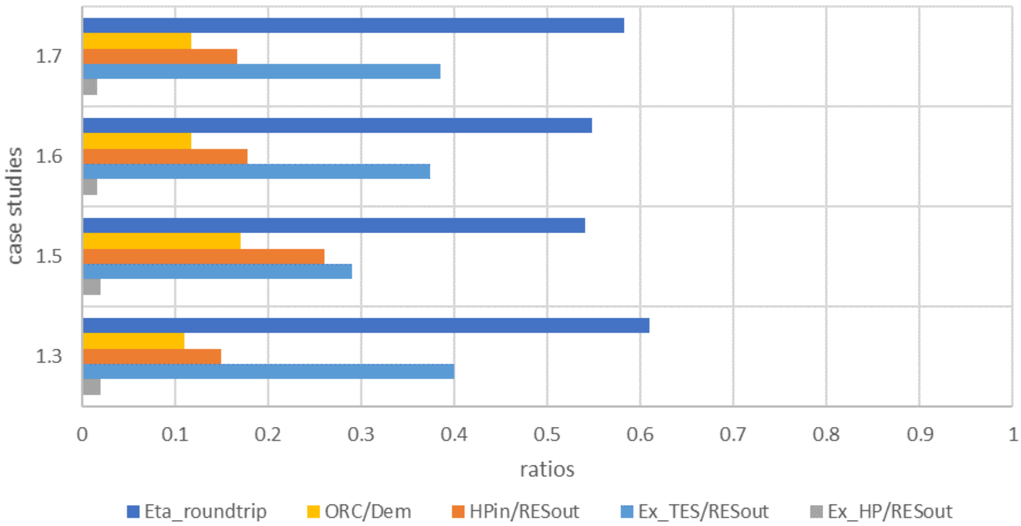


*Figure 21: Simulation results of case studies 1.3, 1.5 1.6 and 1.7.*

Figure 22, Figure 23, Figure 24 and Figure 25 show the level of charge of each storage for case studies 1.3, 1.5, 1.6 and 1.7, respectively. In Figure 22, it can be seen that usually the sensible storage is fully discharged, whereas the latent storage is partially charged.

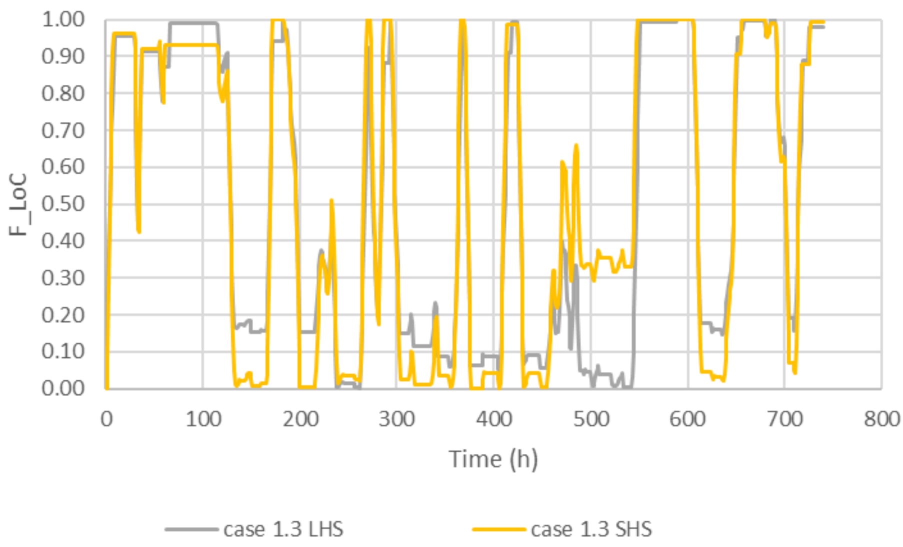


*Figure 22: Level of charge of SH-TES and LH-TES. Case study 1.3.*

In Figure 23, it can be seen just the opposite behaviour, doubling the storage volume of both storages, the LH-TES is fully discharged whereas the SH-TES is partially charged.

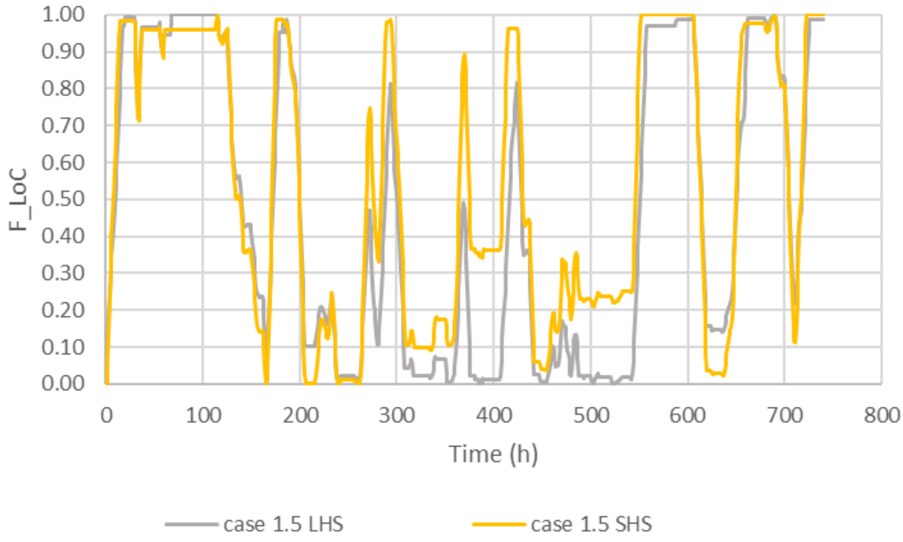


*Figure 23: Level of charge of SH-TES and LH-TES. Case study 1.5.*

In Figure 24 and Figure 25, it can be seen that increasing the volume of only one storage has a negative impact on the charging and discharging processes of the tanks, because always one of them it is not completely discharged.

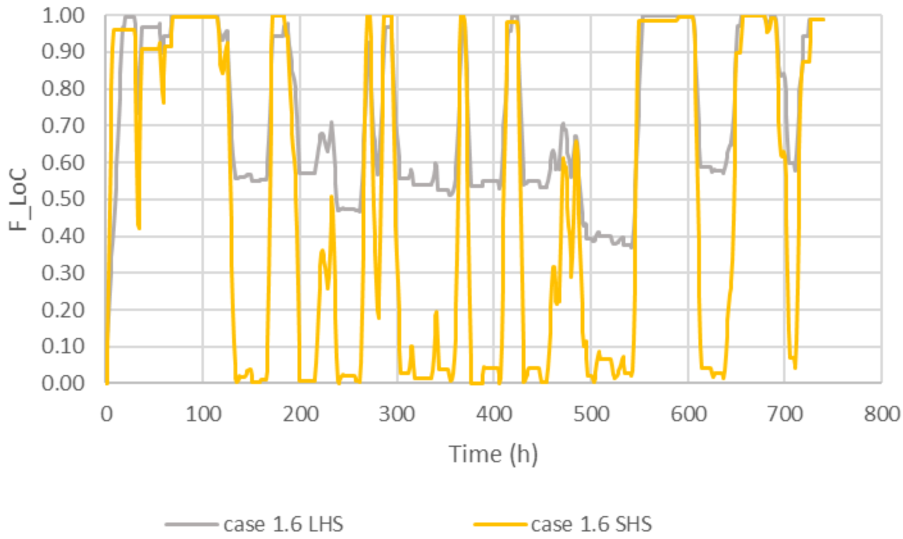


*Figure 24: Level of charge of SH-TES and LH-TES. Case study 1.6.*

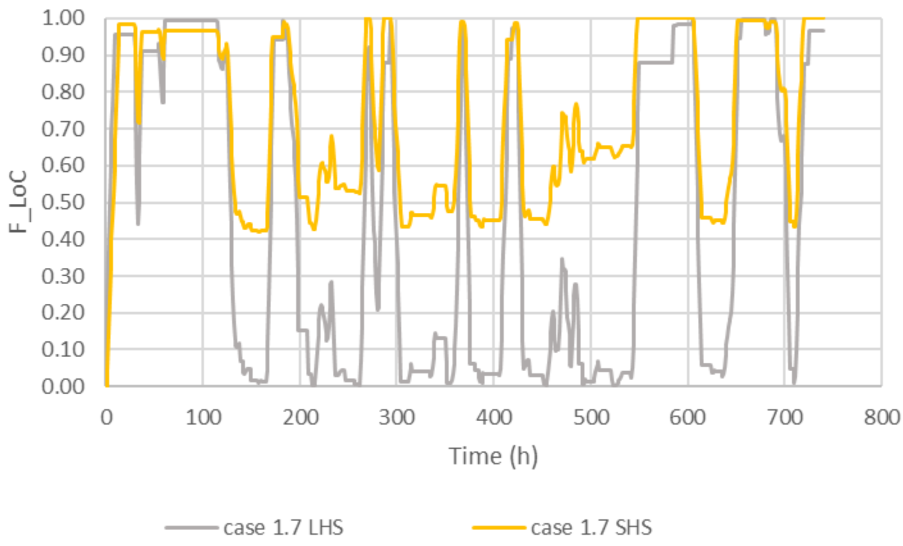


*Figure 25: Level of charge of SH-TES and LH-TES. Case study 1.7.*

## 4.4 Mode 2 Results

Working mode 2, will be suitable if a higher round trip efficiency is needed, of 100%. This operation mode can be achieved by reducing the temperature of the ORC heat dissipation (condensation inlet temperature) to 10ºC by means of using sea water or ambience as heat sink, while assuming that this heat will be extracted from the system (lost). This is the reason why this working mode is suitable for transition periods, when the heat demand of the DH is lower.

Table 14 shows the different case studies that have been defined for operation mode 2. In these cases, transitional scenario, 2MW HP, 1MW ORC and a ratio of 1.2 between the total amount of electrical energy provided by the RES and the total amount of electrical energy demanded by the system have been selected as framework. The parameters that have been studied are: condensation inlet temperature, sensible and latent storage capacities. The same analysis procedure as in working mode 1 was applied.

*Table 14: Case studies for working mode 2.*

| CASE | Season/Scenario | RESel/Dem.el | Mode | HP MW | ORC MW | SH-TES $m^3$ | LH-TES MWh | Tin_cond_ORC ºC |
|---|---|---|---|---|---|---|---|---|
| **2.1** | Transitional | 1.2 | 2 | 2 | 1 | 300 | 30 | 10 |
| **2.2** | Transitional | 1.2 | 2 | 2 | 1 | 300 | 30 | 12.5 |
| **2.3** | Transitional | 1.2 | 2 | 2 | 1 | 300 | 30 | 15 |
| **2.4** | Transitional | 1.2 | 2 | 2 | 1 | 450 | 45 | 10 |
| **2.5** | Transitional | 1.2 | 2 | 2 | 1 | 600 | 60 | 10 |
| **2.6** | Transitional | 1.2 | 2 | 2 | 1 | 300 | 15 | 10 |
| **2.7** | Transitional | 1.2 | 2 | 2 | 1 | 450 | 30 | 10 |
| **2.8** | Transitional | 1.2 | 2 | 2 | 1 | 600 | 30 | 10 |

As shown in Figure 26, as the ambient temperature increases from 10ºC to 12.5ºC and to 15ºC degrees, the round trip efficiency decreases progressively from 1 to 0.925, and the ratio between the net electrical energy output by ORC and the total amount of electrical energy demanded, from 0.15 to 0.13

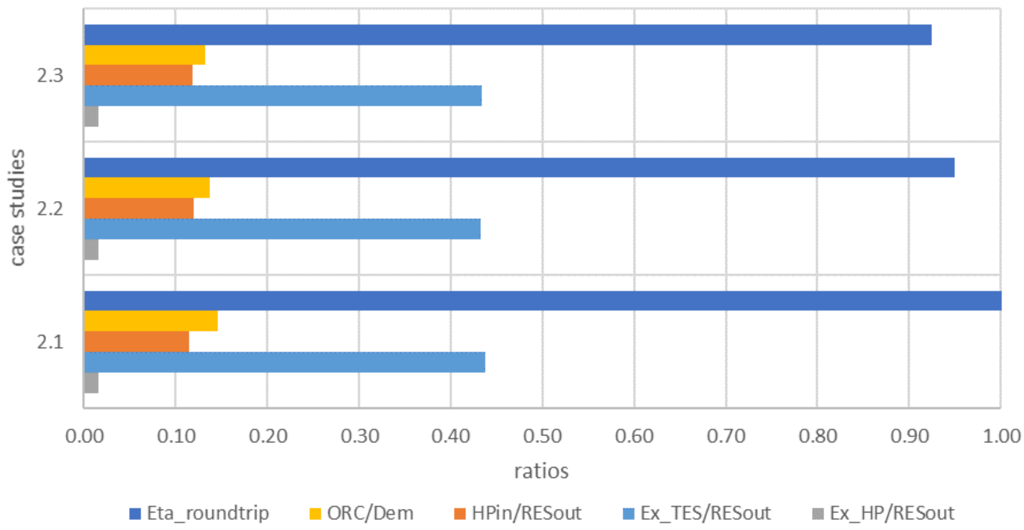


*Figure 26: Simulation results of case studies 2.1, 2.2 and 2.3.*

Figure 27 shows the level of charge of the SH-TES and LH-TES for case study 2.1, which is representative also for case studies 2.2 and 2.3 (same TES volume). In this figure, it can be seen how the sensible heat storage has been fully discharged whereas the LH-TES is partially charged to around 0.4.

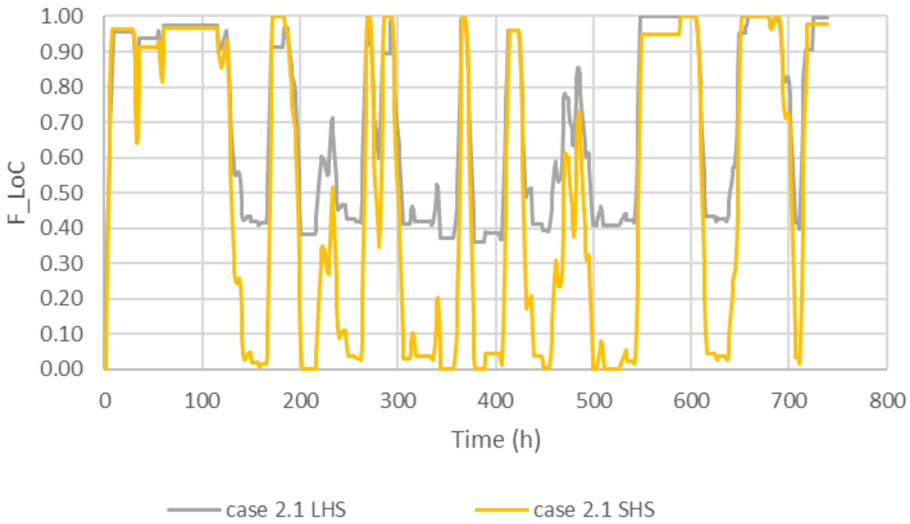


*Figure 27: Level of charge of SH-TES and LH-TES. Case study 2.1.*

Figure 28 shows a comparison between case studies 2.1, 2.4 and 2.5, where it can be seen how the ratio between the net electrical energy output by the ORC and the total amount of electrical energy demanded, increases from 0.15 to 0.22 when the volume of TES increases. However, the round trip efficiency value decreases a little bit from 1 to 0.98. The main reason for this behavior is that the evaporation temperature of the heat pump will also tend to decrease, as it can be seen in Figure 29.

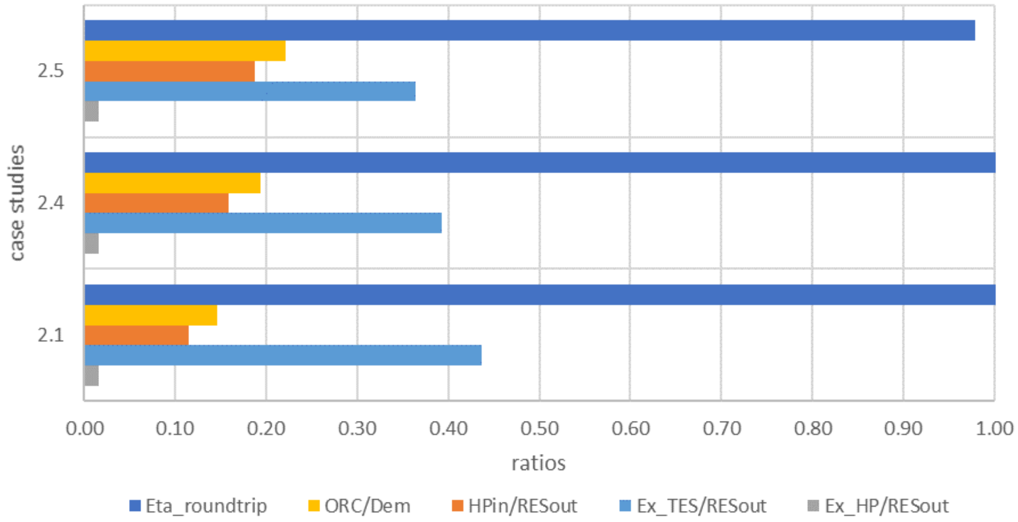


*Figure 28: Simulation results of case studies 2.1, 2.4 and 2.5.*


*Figure 29: HP evaporator water inlet temperature of case studies 2.1, 2.4 and 2.5.*

Figure 30 and Figure 31 shows the level of charge of the TES for case studies 2.1, 2.4 and 2.5. It can be observed from these figures that there is a clear tendency that when the SH-TES is fully discharged the LH-TES is still partially charged (at around 0.4).

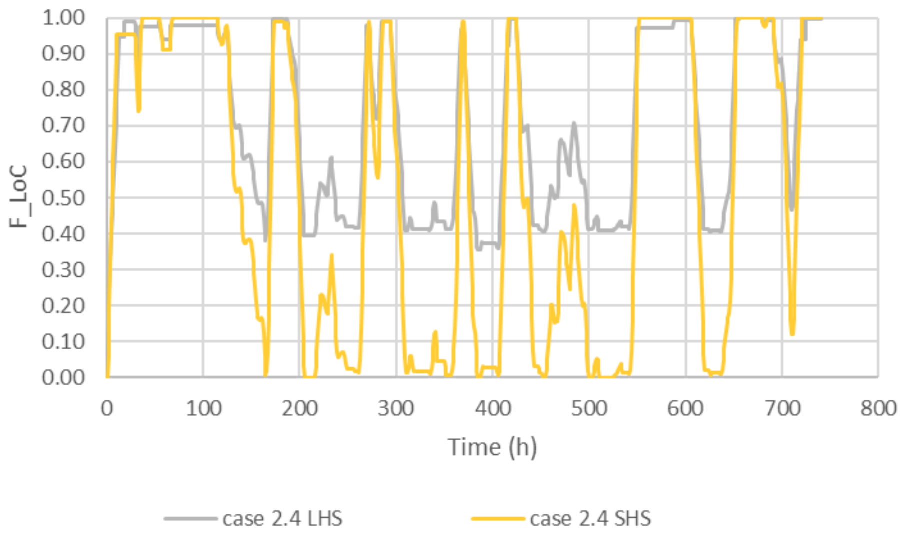


*Figure 30: Level of charge of SH-TES and LH-TES. Case study 2.4.*

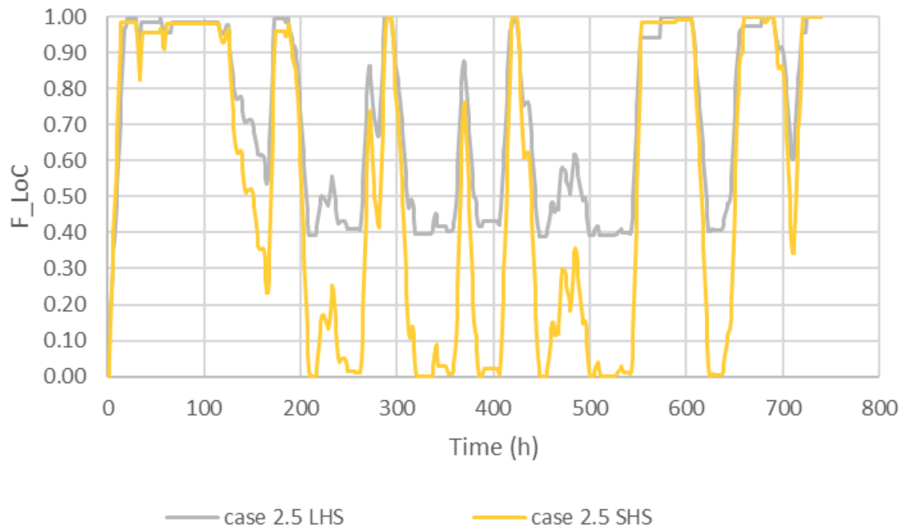


*Figure 31: Level of charge of SH-TES and LH-TES. Case study 2.5.*

In order to improve the behaviour of the LH-TES, case studies 2.6, 2.7 and 2.8 have been run. In these cases, the volume combination of SH-TES and LH-TES has been 300m$^3$/15MWh, 450m$^3$/30MWh and 600m$^3$/30MWh, respectively. Figure 32 shows how the ratio between the net electrical energy output by the ORC and the total amount of electrical energy demanded, increases from 0.13 to 0.20. And the ratio between the excess electrical energy from RES that cannot be used due to TES´s size restrictions, and the total amount of electrical energy output from the RES, decreases from 0.45 to 0.39.

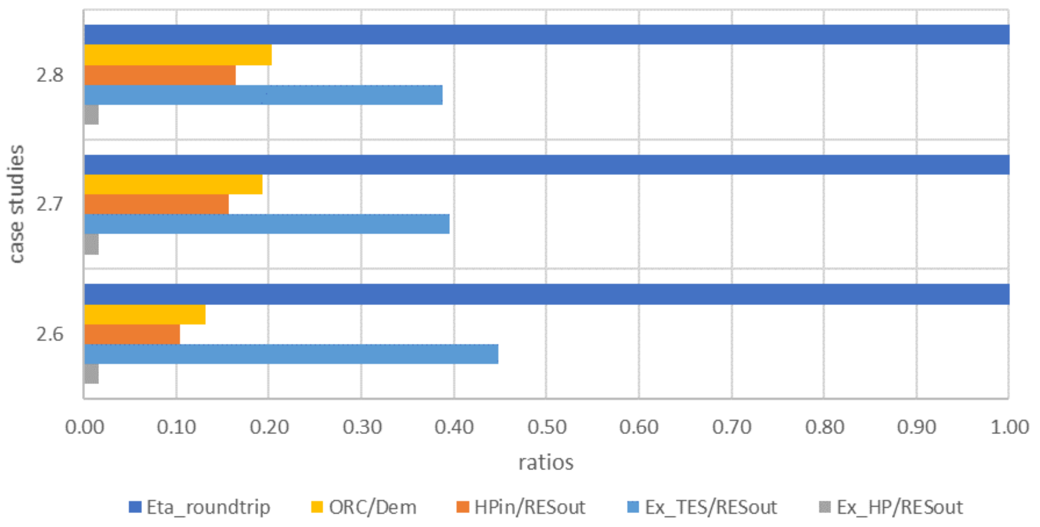


*Figure 32: Simulation results of case studies 2.6,2.7 and 2.8.*

As it can be seen in Figure 33 and in Figure 35, with a ratio of 20 (SH-TES $m^3$/MWh LH-TES), the LH-TES has been fully discharged whereas the SH-TES is partially charged (at a level of around 0.2). This behaviour is more interesting than the behaviour seen in case study 2.1 and 2.7.

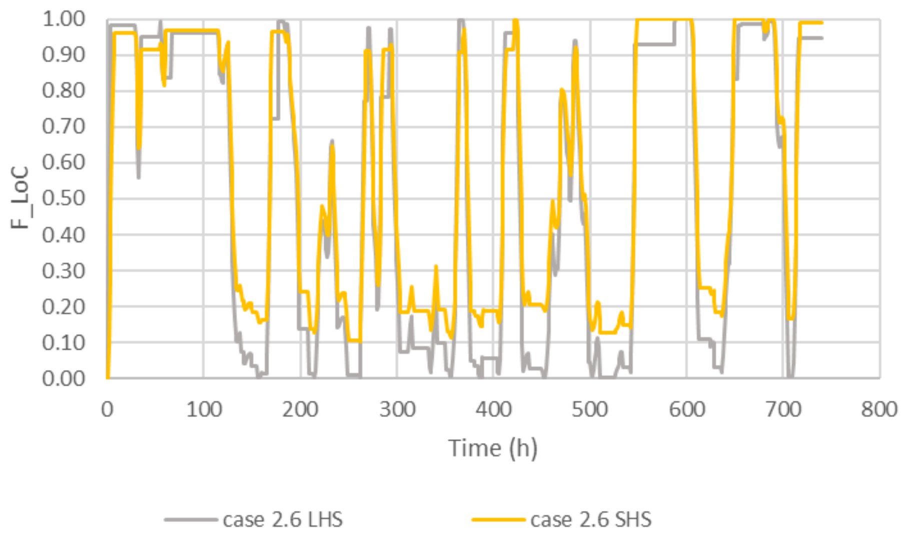


*Figure 33: Level of charge of SH-TES and LH-TES. Case study 2.6.*

However, Figure 34 shows the same behaviour as case study 2.1 (see Figure 27), where the latent storage was fully discharged while the SH-TES is still partially charged. These case studies have a ratio of 10 and 15 (SH-TES $m^3$/MWh LH-TES).

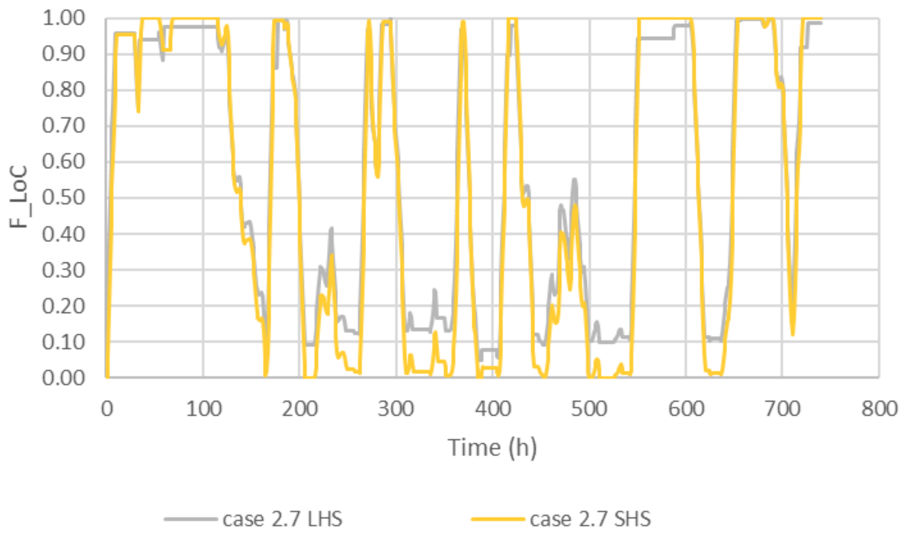


*Figure 34: Level of charge of SH-TES and LH-TES. Case study 2.7.*

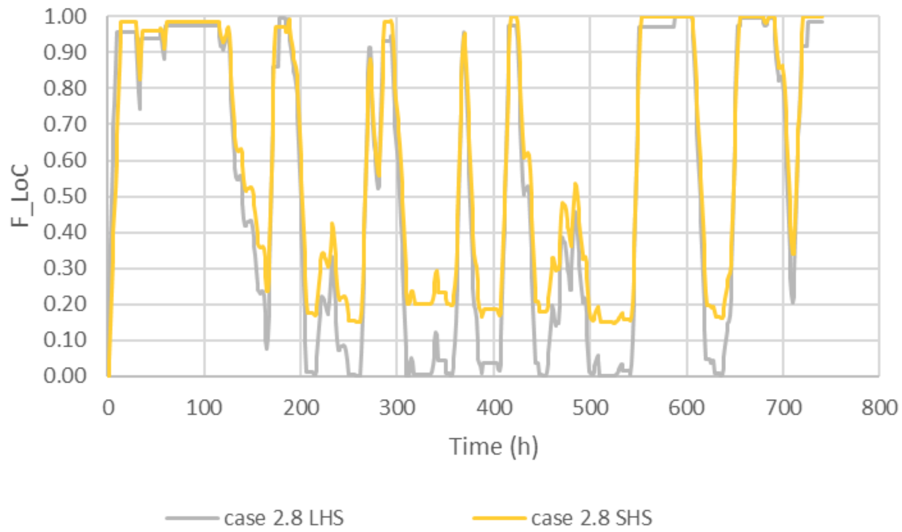


*Figure 35: Level of charge of SH-TES and LH-TES. Case study 2.8.*

## 4.5 Mode 3 Results

Working mode 3 will be also suitable for evaluating the possibility to achieve a round trip efficiency of 100% while considering other boundary conditions than the ones considered in working mode 2. For example, using higher temperature RES heat sources. In this case, it is considered the increasement of the evaporation temperature of the heat pump up to around 100$^{o}$C, suitable to represent the summer or transitional periods.

Table 15 shows the different case studies that have been defined for operation mode 3. In these cases, 2MW HP, 1MW ORC and an evaporation temperature of 100$^{o}$ have been selected as framework. The parameters that have been studied are: two profiles transitional period and summer time, while considering different combinations of SH-TES and LH-TES storage capacity.

*Table 15: Case studies for working mode 3.*

| CASE | Season/Scenario | RESel/Dem.el | Mode | HP MW | ORC MW | SH-TES $m^3$ | LH-TES MWh | Tin_evap_HP $^oC$ (Tcond) |
|---|---|---|---|---|---|---|---|---|
| **3.1** | Transitional | 1.2 | 3 | 2 | 1 | 300 | 30 | 100 |
| **3.2** | Transitional | 1.2 | 3 | 2 | 1 | 300 | 15 | 100 |
| **3.3** | Summer | 1.75 | 3 | 2 | 1 | 300 | 15 | 100 |
| **3.4** | Summer | 1.75 | 3 | 2 | 1 | 600 | 30 | 100 |
| **3.5** | Summer | 1.75 | 3 | 2 | 1 | 300 | 15 | 100 (40$^o$C) |

For case studies 3.1 and 3.2, transitional scenarios and a combination of SH-TES/LH-TES of 300m$^3$/30MWh and 300m$^3$/15MWh were considered. When analysing the different operational ratios, it can see that the results are very similar from one case to the other, as it can be seen in Figure 36. However, the level of charge observed for case study 3.2 seems to be more suitable for being considered in the CHEST system (see in Figure 38).

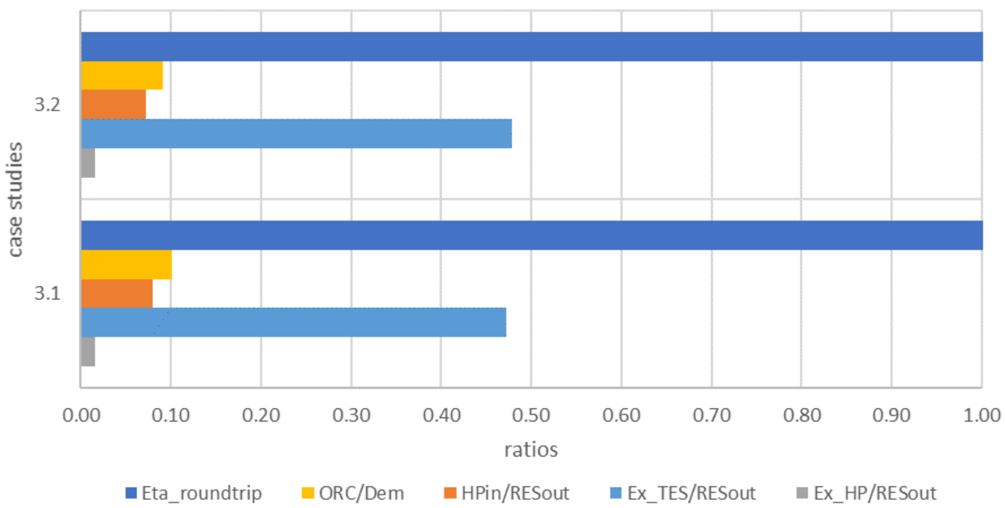


*Figure 36: Simulation results of case studies 3.1 and 3.2.*

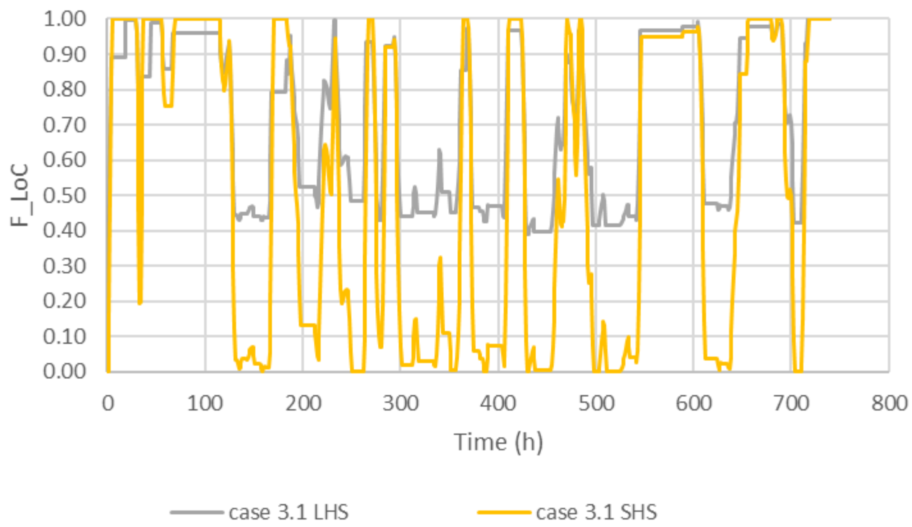


*Figure 37: Level of charge of SH-TES and LH-TES. Case study 3.1.*

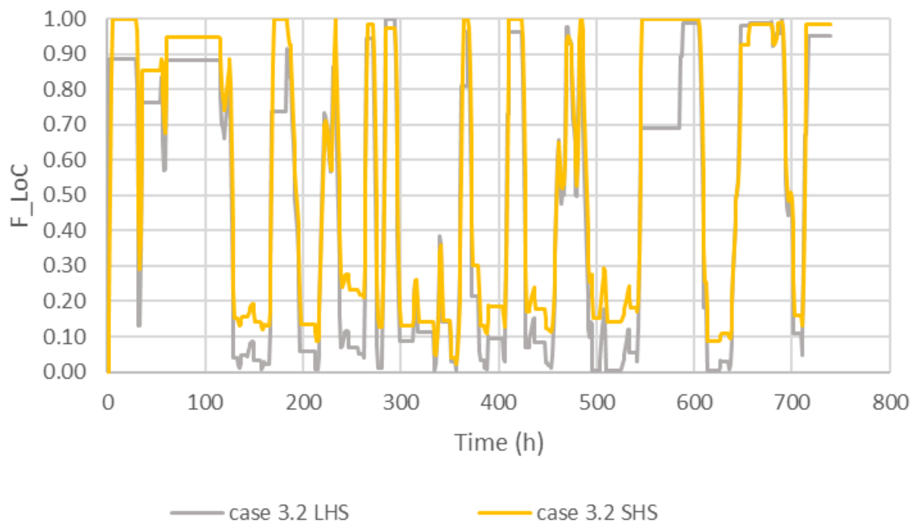


*Figure 38: Level of charge of SH-TES and LH-TES. Case study 3.2.*

Case studies 3.3, 3.4 and 3.5 are defined for a summer period, which means different thermal and electrical profiles (see Annex B) and more electrical and thermal energy excess.

Figure 39 shows the results obtained from case studies 3.3 and 3.4, summer period and a combination of SH-TES/LH-TES of 300m$^3$/15MWh and 600m$^3$/15MWh. For both cases, the round trip efficiency has the same value 0.85 whereas for case study 3.4, the results of ratio between the net electrical energy output by ORC and the total amount of electrical energy demanded by the system and the ratio between the electrical energy consumed by HP and the total amount of electrical energy output from the RES have increased.

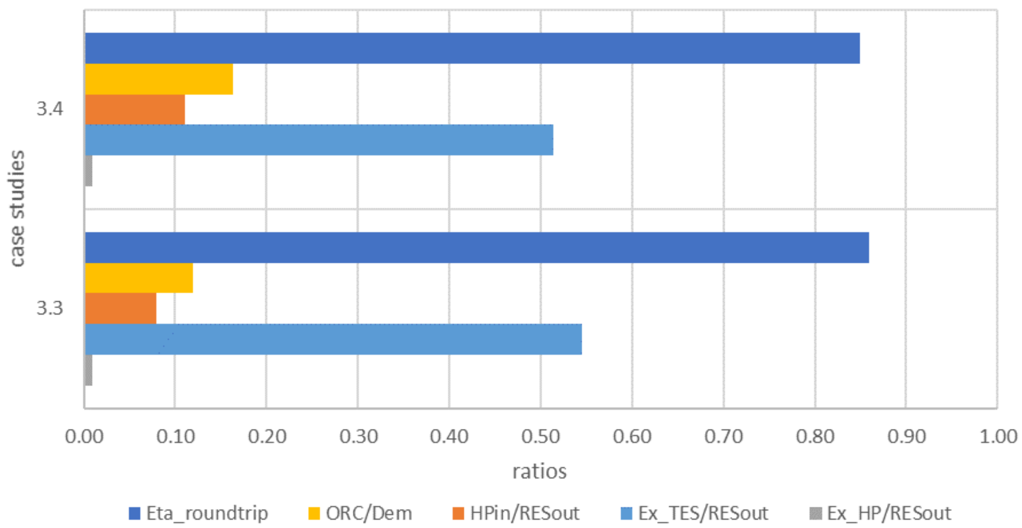


*Figure 39: Simulation results of case studies 3.3 and 3.4.*

The main reason why in summer period the roundtrip efficiency is lower than in transition periods is that in summer, the temperature of the PIT storage increased because there is no heating demand and generated energy is higher. This means a decrease in the ORC efficiency.

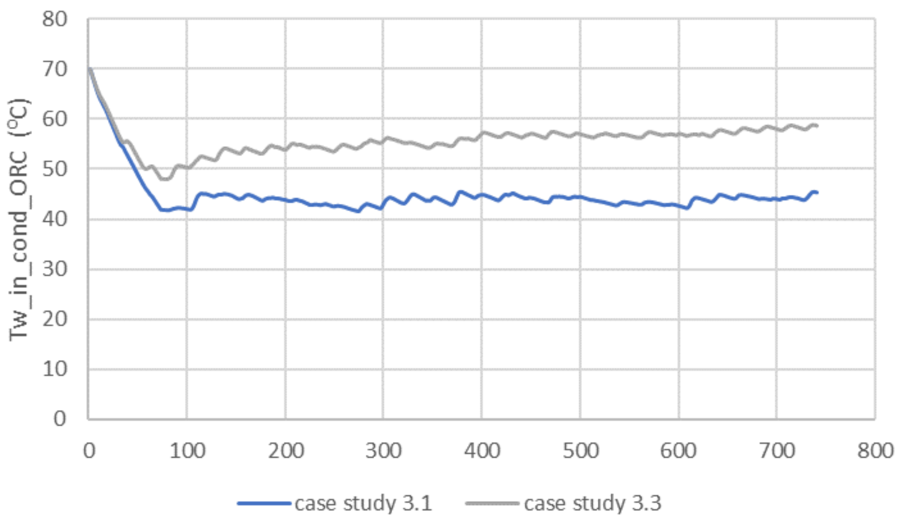


*Figure 40: ORC condensation inlet temperature of case studies 3.1and 3.3.*

If the temperature of the PIT storage remains at 40 $^oC$ (case study 3.5), the results will be better as it can see in Figure 41. In this case, a roundtrip efficiency of 1.15 and the ratio between the net electrical energy output by ORC and the total amount of electrical energy demanded by the system of 0.15 will be obtained.

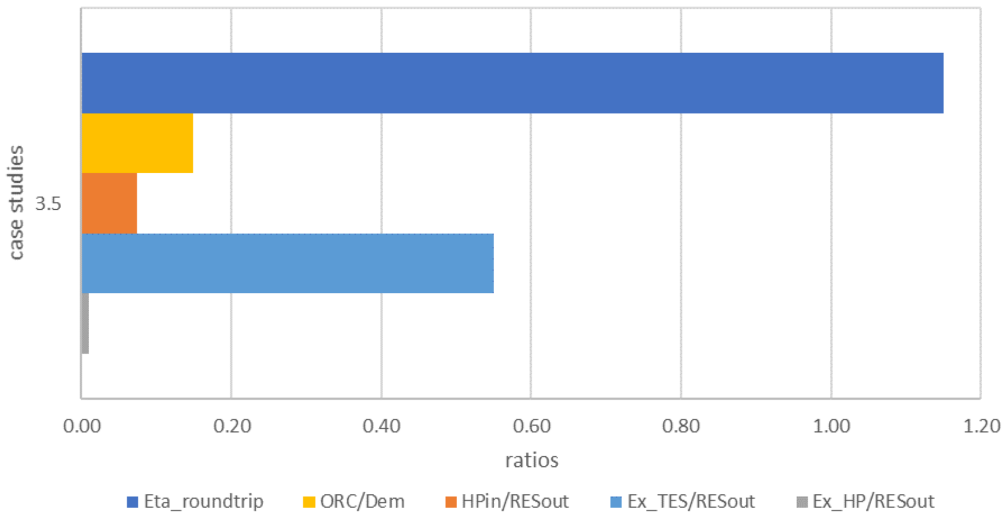


*Figure 41: Simulation results of case studies 3.5.*

## 4.6 Mode 4 Results

This operation mode is a combination of mode 2 and 3. This working mode is suitable when a high electricity demand is needed to be covered by the system, a round trip efficiency higher than 100%. For 1MWhel that the system consumes, it can deliver 1.5MWhel when it is needed, for example at summer time when little demand of DH is needed, and a lot of solar thermal energy is available. In this working mode, sea water will be a suitable heat dissipation sink.
Table 16 shows the different case studies that have been defined for operation mode 4. In these cases, summer scenario, 2MW HP, 1MW ORC, an evaporation temperature of 100$^oC$ and a condensation temperature of 10$^oC$ have been selected as framework.

*Table 16: Case studies for working mode 4.*

| CASE | Season/Scenario | RESel/Dem.el | Mode | HP MW | ORC MW | SH-TES $m^3$ | LH-TES MWh | Tin_evap_HP ºC | Tcond in ORC |
|---|---|---|---|---|---|---|---|---|---|
| **4.1** | Summer | 1.75 | 4 | 2 | 1 | 300 | 15 | 100 | 10 |
| **4.2** | Summer | 1.75 | 4 | 2 | 1 | 600 | 30 | 100 | 10 |

Figure 42 shows a comparison between case studies 4.1 and 4.2, where it can see a small difference by doubling the storage capacity. The ratio between the net electrical energy output by ORC and the total amount of electrical energy demanded, increases from 0.21 to 0.25 when the volume of TES increases. However, the round trip efficiency decreases a little bit from 1.72 to 1.67. The main reason of this behavior is that the evaporation temperature has been decreased as it has been concluded in previous working modes.

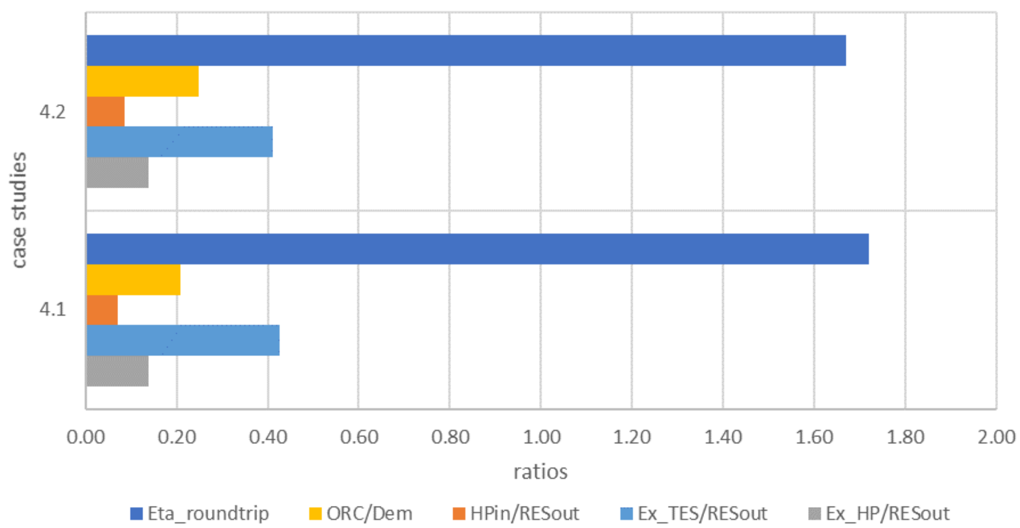


*Figure 42: Simulation results of case studies 4.1 and 4.2.*

Figure 43 and Figure 44 show, the level of charge of the SH-TES and LH-TES for case studies 4.1and 4.2. In both figures, it can see how the latent heat storage has been fully discharged and the sensible heat is partially charged around 0.2. However, in Figure 43 it can see more charging/discharging cycles, because the volume is smaller than in Figure 44.

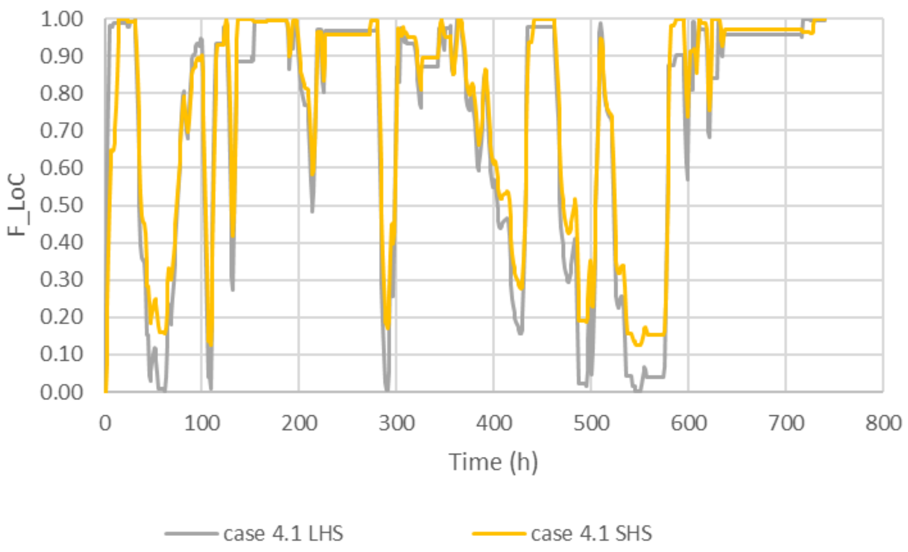


*Figure 43: Level of charge of SH-TES and LH-TES. Case study 4.1.*

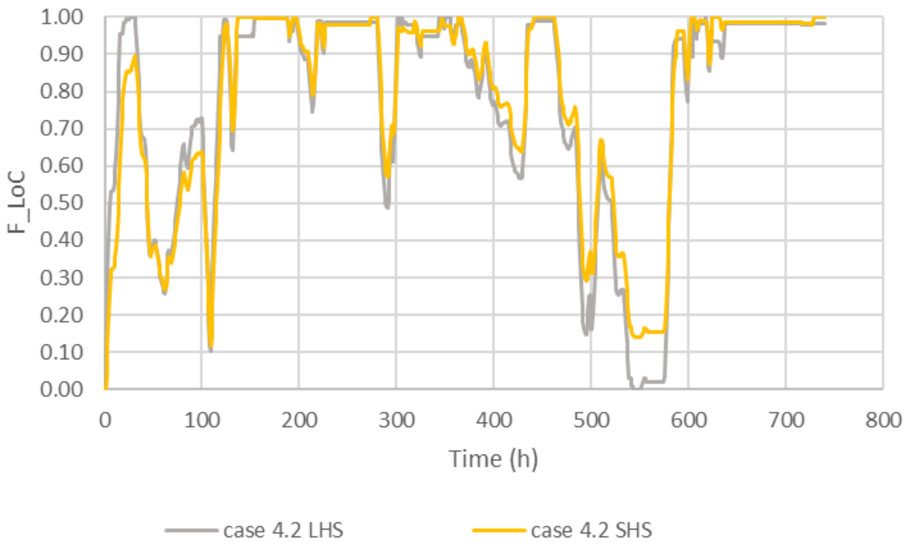


*Figure 44: Level of charge of SH-TES and LH-TES. Case study 4.2.*

## 4.7 Mode 5 Results

This working mode is suitable for winter periods, it provides low round trip efficiency (30%) but increases the temperature of the seasonal thermal energy storage in order to cover the high thermal demand of the district heating. For each MWhel that the system consumes, 0.7MWhth will be converted into heat.

Table 17 shows the different case studies that have been defined for operation mode 5. In these cases, winter scenario, 1MW HP and 1MW ORC have been selected as framework. The parameters that have been studied are different combinations of SH-TES and LH-TES storage capacity as has been done in previous working modes.

*Table 17: Case studies for working mode 5.*

| CASE | Season/Scenario | RESel/Dem.el | Mode | HP MW | ORC MW | SH-TES $m^3$ | LH-TES MWh |
|---|---|---|---|---|---|---|---|
| **5.1** | Winter | 0.8 | 5 | 1 | 1 | 300 | 15 |
| **5.2** | Winter | 0.8 | 5 | 1 | 1 | 150 | 15 |
| **5.3** | Winter | 0.8 | 5 | 1 | 1 | 100 | 10 |
| **5.4** | Winter | 0.8 | 5 | 1 | 1 | 100 | 7.5 |
| **5.5** | Winter | 0.8 | 5 | 1 | 1 | 75 | 5 |

Figure 45 shows the results obtained from case studies 5.1, 5.2, 5.3, 5.4 and 5.5. In this figure it can see how the round trip efficiency is around 0.31-0.32 for all cases whereas, the ratio between the net electrical energy output by ORC and the total amount of electrical energy demanded by the system decreases from 0.04 to 0.01. Besides, the ratio between the electrical energy consumed by HP and the total amount of electrical energy output from the RES decreases from 0.18 to 0.05.

On the other hand, the ratio between the excess electrical energy from RES that cannot be used due to TES´s size restrictions and the total amount of electrical energy output from the RES increases from 0.04 to 0.16.

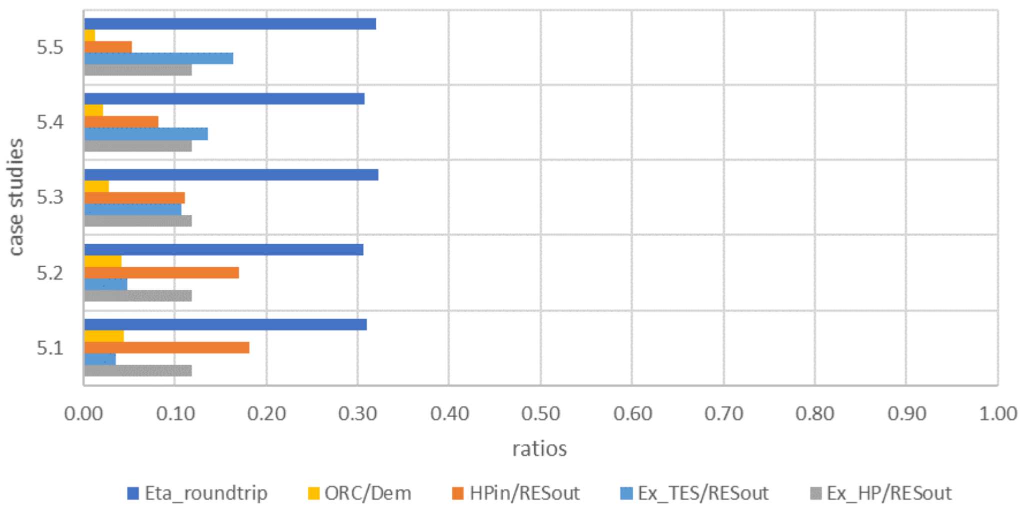


*Figure 45: Simulation results of case studies 5.1, 5 .2, 5.3, 5.4 and 5.5.*

Figure 46, Figure 47, Figure 48, Figure 49 and Figure 50 show the level of charge of sensible and latent heat storages for each case study. In Figure 46, it can see the huge difference between the level of charge of 300$m^3$ SH-TES and 15MWh LH-TES, the latent storage has been fully discharged whereas the SH-TES is still charged.

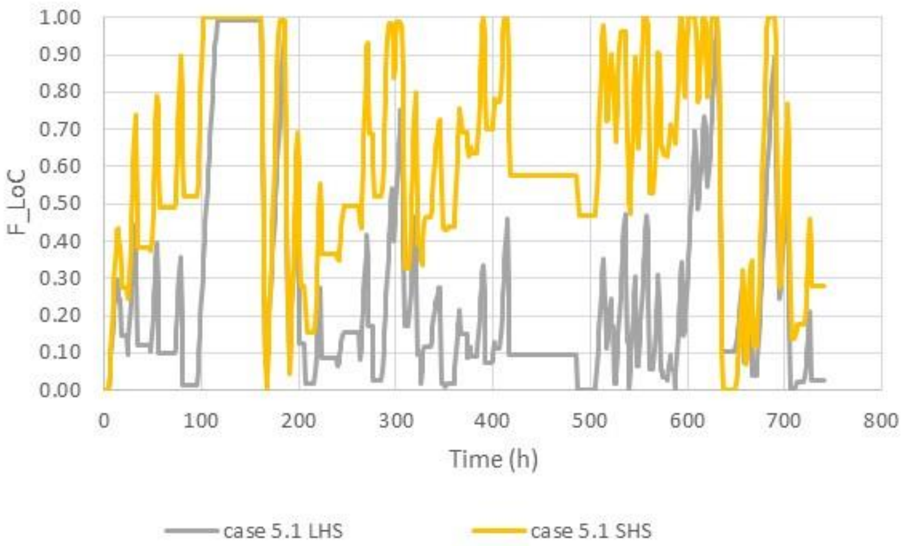


*Figure 46: Level of charge of SH-TES and LH-TES. Case study 5.1.*

Figure 47 shows the level of charge of 150m$^3$ SH-TES and 15MWh LH-TES in this case, the behaviour of both storages is more similar. However, it can see many charging/discharging cycles in the SH-TES.

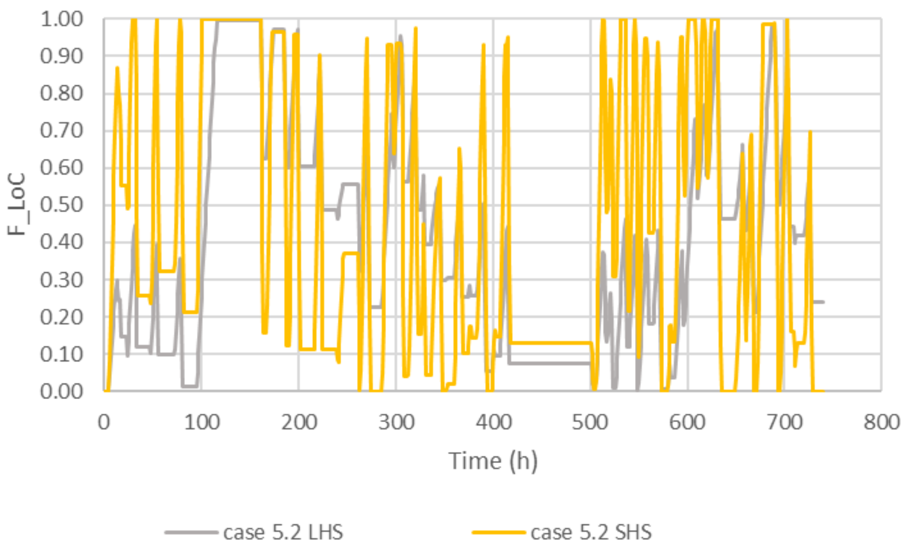


*Figure 47: Level of charge of SH-TES and LH-TES. Case study 5.2.*

Figure 48 shows the level of charge of 100m$^3$ SH-TES and 10MWh LH-TES, in this case it can observe the same behaviour as in Figure 47.

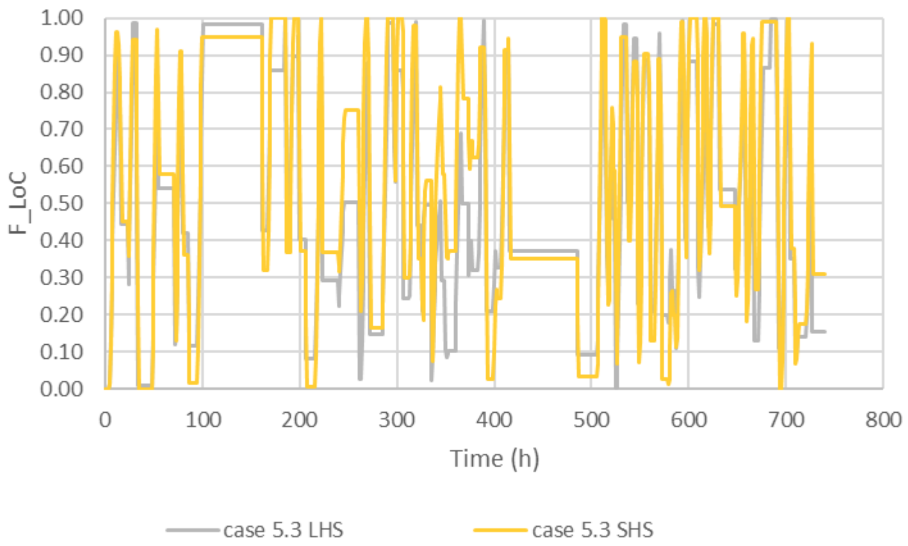


*Figure 48: Level of charge of SH-TES and LH-TES. Case study 5.3.*

Figure 49 and Figure 50 show the level of charge of sensible and latent heat storages for case studies 5.4 and 5.5 respectively. In both cases the latent heat storage has been usually fully discharged whereas the sensible heat storage is partially charged.

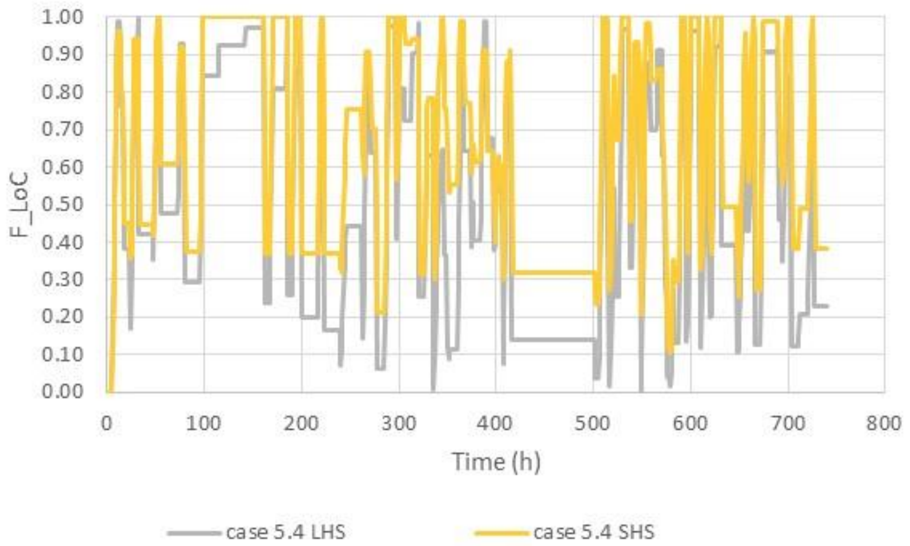


*Figure 49: Level of charge of SH-TES and LH-TES. Case study 5.4.*

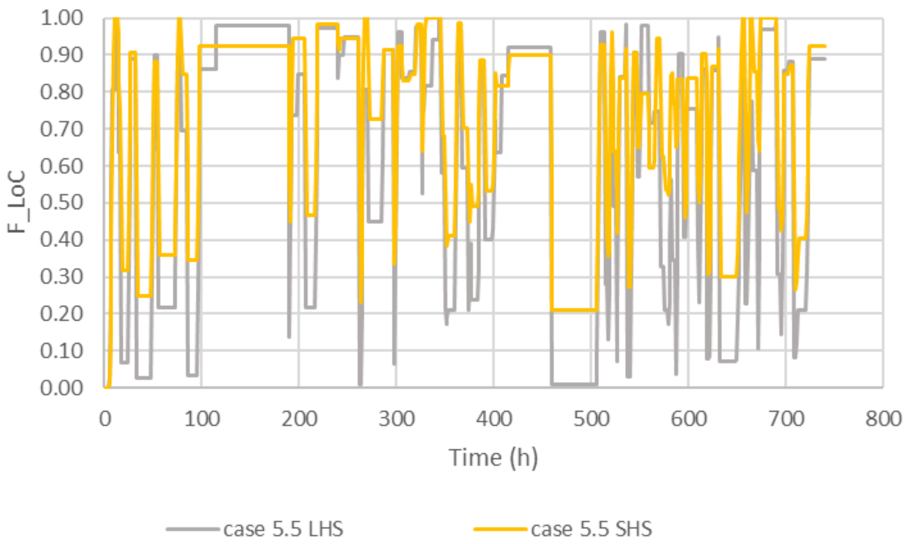


*Figure 50: Level of charge of SH-TES and LH-TES. Case study 5.5.*

## 4.8 Mode 6 Results

This operation mode is similar to operation mode 5, but stronger heating of upper layer of the seasonal TES at lower round trip. It is suitable for weekend or transitional periods when only little electricity energy is needed by industry, but a lot of wind energy is available and heat demand of the district heating is needed.

Table 18 shows the different case studies that have been defined for operation mode 6. In these cases, transitional scenario, 1MW HP and 1MW ORC have been selected as framework. The parameters that have been studied are different combinations of SH-TES and LH-TES storage capacity as has been done in previous working modes.

*Table 18: Case studies for working mode 6.*

| CASE | Season/Scenario | RESel/Dem.el | Mode | HP MW | ORC MW | SH-TES $m^3$ | LH-TES MWh |
|---|---|---|---|---|---|---|---|
| **6.1** | Transitional | 1.2 | 6 | 1 | 1 | 300 | 30 |
| **6.2** | Transitional | 1.2 | 6 | 1 | 1 | 200 | 20 |

Figure 51 shows the results obtained from case studies 6.1 and 6.2. In case study 6.1, the round trip efficiency has a value of 0.2, whereas the ratio between the electrical energy consumed by HP and the total amount of electrical energy output from the RES is 0.25. Besides, the ratio between the electrical energy output by ORC and the total amount of electrical energy demanded by the system is 0.06.

For case study 6.2, the round trip efficiency has a lower value, 0.12; whereas the ratio between the electrical energy consumed by HP and the total amount of electrical energy output from the RES is 0.21. Besides, the ratio between the electrical energy output by ORC and the total amount of electrical energy demanded by the system is 0.05. And, the ratio between the excess electrical energy from RES that cannot be used due to TES´s size restrictions and the total amount of electrical energy output from the RES is 0.21.

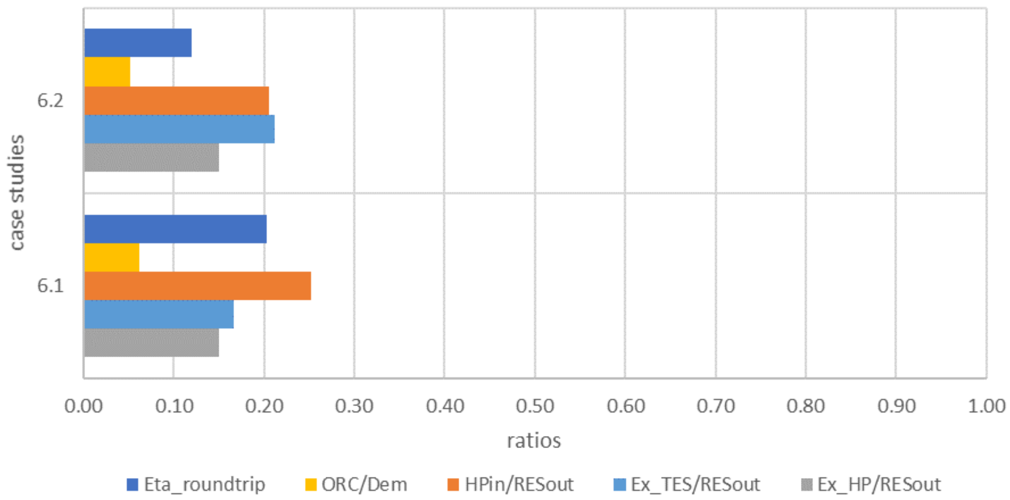


*Figure 51: Simulation results of case studies 6.1 and 6.2.*

Figure 52 and Figure 53 show the level of charge of sensible and latent heat storages for each case study. In Figure 52, it can seen that for a large period of time the LH-TES is fully discharged whereas SH-TES is partially charged at around 0.3-0.5. However, in Figure 53, the behaviour of both storages is more similar.

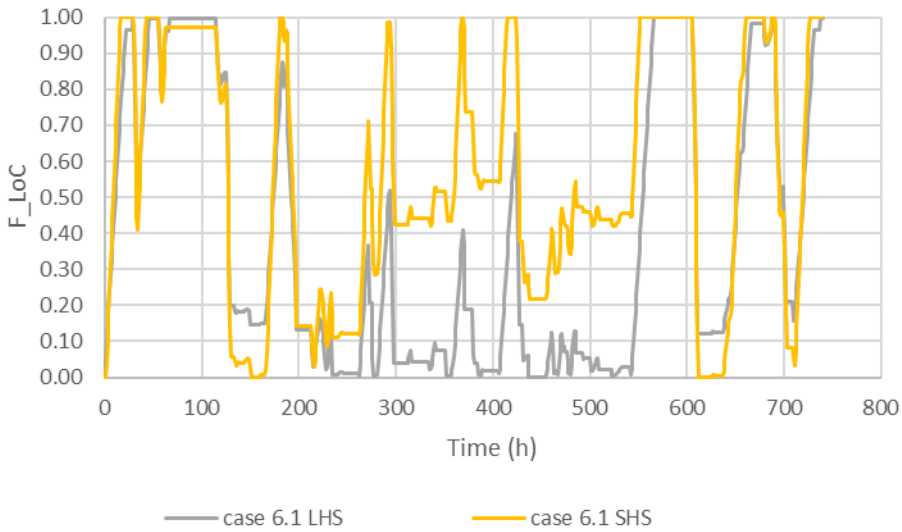


*Figure 52: Level of charge of SH-TES and LH-TES. Case study 6.1.*

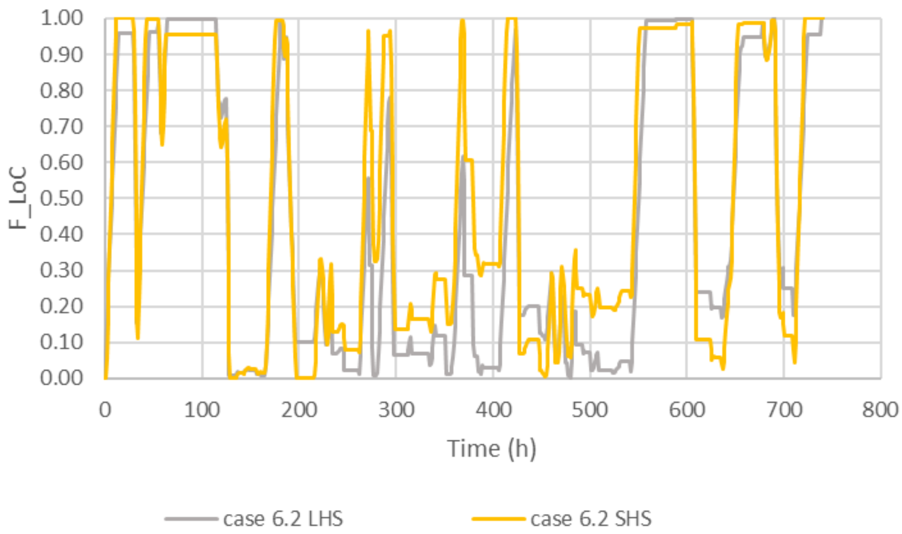


*Figure 53: Level of charge of SH-TES and LH-TES. Case study 6.2.*

# 5 Conclusions

The aim of this deliverable was to define, analyse and evaluate the requirements of the individual technologies that form the CHEST system; a high temperature heat pump, an organic Rankine cycle and a thermal energy storage, which in turn consists of a latent heat storage and sensible heat storage system.

The analysis conducted within this study was performed considering different boundary conditions for the CHEST system. The conclusions generated from this analysis are presented here after, as well as some recommendations for further analyses that might be conducted in the following tasks within the Chester Project.

## 5.1 General Conclusions

The main conclusions considered within this analysis are the following:

- The analysis performed within this deliverable has served to identify potential requirements that the individual technologies that form the CHEST system must consider for both, the large-scale CHEST system and for the CHEST prototype to be developed within WP3 (for further details see the "Technical Conclusions").
- A dedicated TRNSYS model was developed and used within this deliverable to analyse the behaviour of the CHEST concept under different scenarios. This new TRNSYS model, which consists of an upgraded version of the model developed in T2.2 by PlanEnergi, proved to be a useful tool for analysing the behaviour of the CHEST concept under different operating modes. This model is a decoupled model which implies that each component that shape the system is defined individually. This decoupling provides more flexibility to the model and allows analysis at component level as well as system level.
- Six different operating modes[4] were considered for validating the CHEST concept. The operating modes represent different scenarios (different boundary conditions and RES generation/demands profiles) in which the CHEST system was tested by means of the developed TRNSYS simulation tool. The results achieved are very promising, and the CHEST concept has proven to be aligned with the theoretical results expected for those scenarios.
- Based on the results presented in this deliverable, it can be concluded that the CHEST system has a high potential for being applied in different RES scenarios. The CHEST concept 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. However, for each particular scenario, a specific CHEST system must be considered (it must be properly sized and designed).
- Special attention must be put into the available heat source (Thermal RES) when defining and sizing a CHEST system. It must not be forgotten that the CHEST concept relies on the operation of a heat pump, which need both, electrical energy and a heat source supply at the highest possible temperature in order to maintain high efficiency ratios for the whole system operation. Thus, when defining a CHEST system, it is highly recommended to put special attention to the heat source availability, and to efficiently

[4] Operating modes were taken from CHESTER´s Grant Agreement documentation, Annex 1 (part A), section 1.5.1: Overall concept underpinning the project.

match this available heat source with the HP sizing, while always considering the possibility to expand the Thermal RES supply if finally required by the project under study.

## 5.2 Technical Conclusions

The main technical conclusions derived from this analysis are listed here after:

### A. Requirements of the Individual Technologies

According to the technical requirements of the individual technologies that form the CHEST system, the most relevant issues identified within this analysis are the following:

- **Ratio HP vs. ORC:** When high round trip efficiencies are desired (high power-to-heat-to-power ratio), it seems that the HP capacity versus the ORC capacity (sizing ratio) must be increased. Within this study, increasing the sizing ratio from one to two seems to improve the round trip efficiency of the whole system. However, special attention must be paid to the available heat source in the system, because increasing the HP´s capacity will require more Thermal RES to be provided to the HP system, otherwise, the evaporating temperature to the HP might consequently decrease, having a negative impact on the system´s efficiency. On the other hand, when low round trip efficiencies are desired, a sizing ratio of one seems to be adequate. Therefore, it is recommended to consider the analysis of the HP to ORC size in both, the CHESTER prototype analysis and for the large-scale systems to be analysed within WP4´s simulations.
- **TES Storage capacity:** From the simulations performed in this deliverable, it was observed that the sizing of both TES (SH-TES and LH-TES) must be carried out jointly and specifically for each operation mode. Nevertheless, it seems that a ratio of 10m$^3$SH-TES/1MWh LH-TES in these case studies considered suitable.
- **Operating temperature range:** Through these simulations, it has been shown that both the HP and the ORC are prompt to operate in a wide range of temperatures in order to provide maximum flexibility to the CHESTER system. The HP can go from 40ºC to 100ºC in the heat source, and the ORC can condense from 60ºC (or more) up to ambient temperature (e.g. 10ºC). This wide range of operating conditions may have an impact on the design of both systems, especially in the case of the HP, which is a system that usually gets more complicated in its design and operation when prompt to work over a wide range of pressure ratios.
- **Excess heat:** In the simulations performed with the TRNSYS model, it was observed that usually the ratio of charge of the latent heat storage (LH-TES) and the sensible heat storage (SH-TES) seems to be unbalanced, and vice versa. This means that, when one of the storage systems reaches its maximum level of charge, the other one might still haven´t been completely charged. In the simulations, if this situation occurs, the heat pump is forced to continue to operate for reaching a full charge condition for both storages, but an “excess heat” concept is introduced. This excess heat is the amount of heat (either in the latent or the sensible part of the systems) that the charging system is providing in excess, and the TES is not able to store, thus it must be taken out of the system. Therefore, it is recommended that this situation could be further analysed and discussed within WP3 and WP5, in order to have a better understanding of this situation.

- **Control of the HP´s sensible heat system:** A specific analysis on the effect of the hot water temperature supplied to the SH-TES was conducted. The conclusion from this analysis showed that the system´s highest COP was reached when the SH-TES received the hot water from the HP at the maximum possible temperature. Thus, it is recommended that the HP system could provide a control strategy specifically dedicated to this purpose. This means, that the control at the HP´s subcooler component should be implemented in order to provide the water at the highest possible temperature.

**B. Analysis of the CHEST Concept under Six Operating Modes**

The results achieved in the analysis of the CHEST system under the six different operating modes, are the following:

- **Mode 1:** According to working mode 1, which may represent the operation mode of the CHEST system in a transitional period assuming 80ºC as evaporation inlet temperature and 40ºC as condensation temperature; the most suitable configuration seems to be the one considered in case study 1.3. In this case study, a HP power capacity of 2MW, ORC power of 1MW and 300m$^3$ and 30MWh as maximum storage capacity of the LH-TES, were considered.
- **Mode 2:** For case study 2, which is suitable for transitional periods when the ambient air (or for example sea water) can be used as heat sink at around 10ºC while a round trip efficiency of 100% is needed, the most promising configuration will be 2MW for the HP, 1MW for the ORC, 600m3 of SH-TES and a 30MWh LH-TES.
- **Mode 3:** Working mode 3, also suitable for a round trip efficiency of 100%, having an evaporation temperature up to 100ºC. In this case, also considering the transitional scenario, the best combination that has been studied is 2MW for the HP, 1MW for the ORC, 300m$^3$ of SH-TES and a 15 MWh LH-TES. However, in order to obtain a round trip efficiency of 100% in summer time, the low part of the PIT storage must be around 40ºC, otherwise the round trip efficiency will be of around 0.85. The main problem in summer time is that the DH heat demand is low, the solar thermal gain is high and the temperature of the low part of the tank rises (which is related to the condensation temperature for ORC), decreasing the efficiency of the ORC system, and thus of the whole CHEST system.
- **Mode 4:** Working mode 4, when a high electricity demand is needed to be covered by the system, and a round trip efficiency higher than 100% is expected. Assuming 100ºC as evaporation inlet temperature to the HP, and 10ºC as the condensation temperature, the most promising configuration that has been studied considers a 2MW HP, a 1MW ORC system, 300m$^3$ of SH-TES and a 15MWh LH-TES.
- **Mode 5:** In working mode 5, suitable for winter periods, where low round trip efficiencies can be expected (around 30%), the most promising configuration that has been analysed is as follow: 1MW for the HP, a 1 MW ORC system, 100m$^3$ of SH-TES and a 10 MWh LH-TES.
- **Mode 6:** Working mode 6, suitable for transitional periods, when only little electrical energy is needed by the industry, but a lot of wind is available and heat demand of the district heating is needed, the most promising configuration that has been studied is: a 1MW HP, 1MW ORC system, 200m$^3$ of SH-TES and a 20 MWh LH-TES.

Based on the results presented in this deliverable, it can be concluded that the CHEST system has high potential for being implemented in different scenarios and necessities. However, it must be size and design a specific CHEST system for each scenario.

Finally, the model developed within this deliverable will serve:

- as the baseline of the full-scale CHEST system model that will be developed in WP4
- to simulate the CHESTER prototype of WP3 (with few modifications)
- to analyse in detail the problem of Excess Heat (WP3 and WP5)

# 6 Annex A

POWER FILE

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| P_el_out_RES_MW | Output electrical power from RES. | MW |
| P_el_dem_MW | Electrical power demanded. | MW |

CONTROL CARDS

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| P_el_in_nom_HP_MW | Nominal input electrical power for HP's compressor. | MW |
| P_el_net_nom_ORC_MW | Nominal net electrical power output from the ORC. | MW |
| Cp_w_kJ_kgK | Specific heat of water. | kJ/kgK |
| Rho_w_kg_m3 | Density of water. | $kg/m^3$ |
| V_w_SH-TES_m3 | Volume of SH-TES's water tanks. | $m^3$ |
| E_q_max_LH-TES_MWh | Maximum Storage capacity of LH-TES tank. | MWh |
| T_w_in_evap_HP_C | Inlet water temperature (source) to the HP's evaporator. | °C |
| DT_w_evap_HP_K | Water-side temperature difference in the HP's evaporator. | K |
| T_w_in_cond_ORC_C | Inlet water temperature (sink) to the ORC's condenser. | °C |
| DT_w_cond_ORC_K | Water-side temperature difference in the ORC's condenser. | K |
| T_opt_LTWT_user_option_B | Value of T_opt_LTWT set by the user in case the option B is selected. | °C |
| dT_cond_LTWT_option_B | Minimum temperature difference between T_opt_LTWT_user_option_B and T_w_in_cond_ORC_C to ensure that second law of thermodynamics is not being violated during the simulation. | K |

POWER CONTROL

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| P_el_bypass_RES_MW | Bypassed electrical power from the RES (to be delivered directly to the demand side). | MW |
| P_el_surplus_RES_MW | Electrical power surplus from the RES that is available to HP's consumption (after bypass). | MW |
| P_el_def_pass_dem_MW | Deficit power in the demand side after the Bypass from RES. | MW |
| SF_P_el_in_HP | Safety factor to ensure that the electrical power input to the HP is equal or less than the predefined nominal value. | - |
| SF_P_el_net_ORC | Safety factor to ensure that the net electrical power output from the ORC is equal or less than the predefined nominal value. | - |
| P_el_in_est_HP_MW | Estimated power input to the HP (considering only the HP's nominal value restrictions). | MW |
| P_el_net_est_ORC_MW | Estimated net electrical power output from the ORC (considering only the ORC's nominal value restrictions). | MW |
| P_el_in_HP_MW | Actual electrical power input to the HP (considering both HP and TES sizing restrictions). | MW |
| P_el_net_ORC_MW | Actual net electrical power output from the ORC (considering both ORC and TES sizing restrictions). | MW |

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| F_ctrl_char_TES | Factor to control the actual electrical input power to the HP. | - |

[HT-HP] SCALE & SIZE

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| P_q_lat_est_HP_MW | Estimated latent heat to be delivered by the HP after scaling (based on size and capacity factors F_size_nom_HP and F_q_capacity_PLR_HP) | MW |
| P_q_sen_est_HP_MW | Estimated sensible heat to be delivered by the HP after scaling (based on size and capacity factors F_size_nom_HP and F_q_capacity_PLR_HP) | MW |
| F_size_nom_HP | Factor used to re-size the HP in case of a nominal power different than 1 MW. | - |
| F_q_capacity_PLR_HP | Factor used to scale the HP's thermal capacity in the case of partial load conditions. | - |
| F_PLR_HP | Partial Load Ratio (PLR). Coefficient between the actual power and the nominal power of the heat pump used to determine the actual COP when working at partial load. | - |
| COP_HP | Actual COP of the HP. | - |
| P_q_tot_est_HP_MW | Estimated total heat to be delivered by the HP after scaling. | MW |
| P_q_tot_nom_HP_MW | Nominal total heat delivered by the HP. | MW |

[ORC] SCALE & SIZE

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| F_capacity_PLR_ORC | Factor used to scale the thermal capacity consumed by the ORC in the case of partial load conditions. | - |
| F_size_nom_ORC | Factor used to re-size the ORC in case of a nominal power different than 1 MW. | - |
| P_q_lat_est_ORC_MW | Estimated latent heat consumed by the ORC after scaling (based on size and capacity factors F_capacity_PLR_ORC and F_size_nom_ORC). | MW |
| P_q_sen_est_ORC_MW | Estimated sensible heat consumed by the ORC after scaling (based on size and capacity factors F_capacity_PLR_ORC and F_size_nom_ORC) | MW |
| P_q_cond_ORC_MW | Heat capacity for the ORC´s condenser. | MW |

[TES] CONTROL

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| F_char_LH-TES | Factor used to permit the charging of TES if there is sufficient remaining capacity in the latent storage (0 or 1). | - |
| F_dchar_LH-TES | Factor used to permit the discharging from TES if there is sufficient latent capacity stored to power on the ORC (0 or 1). | - |
| F_char_V_SH-TES | Factor used to permit the charging of TES if there is sufficient remaining water volume in the sensible storage (0 or 1). | - |
| F_dchar_V_SH-TES | Factor used to permit the discharging from TES if there is | - |

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| | sufficient remaining water volume in the sensible storage to power on the ORC (0 or 1). | |
| P_q_lat_TES_MW | Latent heat charged/discharged from TES (considering TES controls) | MW |
| P_q_sen_char_TES_MW | Sensible heat charged in the TES (considering TES controls) | MW |
| P_q_sen_dchar_TES_MW | Sensible heat discharged from the TES (considering TES controls) | MW |
| m_est_subc_HP_kg_s | Estimated water mass flow rate inside HP´s subcooler (based on the estimated sensible heat to be charged). This variable is used to calculate F_char_V_sen_TES. | kg/s |
| m_est_preh_ORC_kg_s | Estimated water mass flow rate inside ORC´s preheater (based on the estimated sensible heat to be discharged). This variable is used to calculate F_dchar_V_sen_TES | kg/s |

[TES] LH-TES

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| T_melt_PCM_C | Melting temperature of PCM inside the LH-TES. | °C |
| F_LoC_LH-TES | Factor used to identify the level of charge (LoC) of the LH-TES tank (liquid fraction of the PCM). | - |
| E_q_lat_TES_MWh | Latent energy stored in the TES. | MWh |
| P_q_lat_excess_HP_MW | Excess latent heat of the HT-HP | MW |

[TES>SH-TES] TANKS PARAMETERS

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| r_DtoH_SH-TES | Diameter-to-height ratio of the SH-TES tanks. | - |
| U_HTWT_SH-TES | Loss coefficient for HTWT. | kJ/h $m^2K$ |
| U_LTWT_SH-TES | Loss coefficient for LTWT. | kJ/h $m^2K$ |

[TES>SH-TES] HIGH-TEMP WATER TANK

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| T_w_HTWT_SH-TES_C | Temperature of water contained in the high-temperature water tank (HTWT). | °C |
| V_w_HTWT_SH-TES_m3 | Volume of water contained in the HTWT. | $m^3$ |
| m_w_preh_HP_kg_h | Mass flow rate of water out from the HTWT. | kg/h |

[TES>SH-TES] LOW-TEMP WATER TANK

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| T_w_LTWT_SH-TES_C | Temperature of water contained in the low-temperature water tank (LTWT). | °C |
| V_w_LTWT_SH-TES_m3 | Volume of water contained in the LTWT. | $m^3$ |
| m_w_subc_HP_kg_h | Water mass flow rate out from LTWT. | kg/h |

[TES>SH-TES] CHARGING-SIDE

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| T_w_out_subc_HP_C | Temperature of water at the outlet of the subcooler. | °C |
| m_w_dem_subc_HP | Mass flow rate demanded by subcooler to the LTWT. | kg/h |
| F_LoC_SH-TES | Factor used to identify the level of charge of SH-TES (level of water contained in the hot tank). | - |
| m_w_subc_HP_kg_h | Actual water mass flow rate inside subcooler. | kg/h |
| P_q_excess_HP_MW | Heat expelled in the excess heat exchanger of the HT-HP | MW |

[TES>SH-TES] DISCHARGING-SIDE

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| T_w_out_preh_ORC_C | Temperature of water at the outlet of the preheater. | °C |
| m_w_dem_preh_ORC | Mass flow rate demanded by preheater to the HTWT. | kg/h |
| SF_T_dchar_HTWT | Safety factor to ensure that the outlet water temperature from HTWT is close to 133 °C (melting temperature). | - |
| m_w_preh_ORC_kg_h | Actual water mass flow rate inside preheater. | kg/h |

GLOBAL PERFORMANCE

| VARIABLE NAME | DESCRIPTION | UNITS |
|---|---|---|
| Eta_roundtrip_CHEST | Roundtrip efficiency of the CHEST system | - |
| E_el_out_RES | Total amount of electrical energy output from the RES. | MWh |
| E_el_dem | Total amount of electrical energy demanded. | MWh |
| E_el_bypass_RES | Total amount of electrical energy bypassed from RES during the simulation time. | MWh |
| E_el_surplus_RES | Surplus electrical energy from the RES that is available to HP's consumption (after bypass). | MWh |
| E_el_def_dem_bypass | Deficit in the demand-side after the bypassed energy. | MWh |
| E_el_in_HP | Actual electrical energy consumed by HP. | MWh |
| E_el_ex_RES_size_HP | Excess electrical energy from RES that cannot be used due to HP's size restriction (predefined nominal power). | MWh |
| E_el_ex_RES_size_TES | Excess electrical energy from RES that cannot be used due to TES's size restriction. | MWh |
| E_el_net_ORC | Actual net electrical energy output from the ORC. | MWh |
| E_el_def_tot_dem | Total deficit in the demand-side, that is not covered by either the bypassed energy or CHEST system. | MWh |
| E_q_sen_excess_HP | Sensible energy expelled during the functioning of the HT-HP. | MWh |
| E_q_lat_excess_HP | Latent energy expelled during the functioning of the HT-HP. | MWh |

# 7 Annex B

## 7.1 HT-HP Performance Map[5]

The independent variables used for the HT-HP map are, as aforementioned, $T_{in_{evap}}$, $\Delta T_{evap}$ and $T_{LTWT}$. While the range of the temperatures in the evaporator is selected according to the working modes of the CHEST system, the range of $T_{LTWT}$ is the temperature of the tank in the timestep that is being evaluated, and is in the range from the ambient temperature to the maximum value that it is expected to reach:

*Table 19: Temperature ranges for HT-HP performance map.*

| Variable | Values (°C) | | | | |
|---|---|---|---|---|---|
| $T_{w\_inlet\_evap}$ | 40 | 55 | 70 | 85 | 100 |
| $\Delta T_{w\_evap}$ | 2 | 4 | 6 | | |
| $T_{LTWT}$ | 25 | 55 | 70 | 85 | 100 |

Thus, the total number of points of this map is $5^2$*3= 75.

The TRNSYS-CHEST has the following inputs for the performance map:

- **T_w_in_evap_HP_C**: Variable located in *CONTROL CARDS* that can be modified by the user according to the working mode that is desired to be simulated.
- **DT_w_evap_HP_K**: Also modified by the user, in *CONTROL CARDS*.
- **T_w_LTWT_SH-TES_C:** Temperature of the cold tank at that time step. The map will use this temperature to provide the heat needed to reach the optimum output temperature in the subcooler (fixed at 133°C).

The outputs obtained in the map that are employed in the TRNSYS-CHEST model are:

- **P_q_sen_nom_HP_MW:** Nominal sensible heat delivered by the HT-HP with a nominal input power of 1MWe, to be stored in the SH-TES storage tanks, in MW.
- **P_q_lat_nom_HP_MW:** Nominal latent heat delivered by the HT-HP with a nominal input power of 1MWe, to be stored in the LH-TES storage tank, in MW.
- **COP_nom_HP:** Nominal COP for the HP with a nominal input power of 1 MWe.

These outputs are calculated for a nominal input power in the compressor of the HT-HP of 1 MWe working at full load. Later on, these values are adjusted in case the input power differs from 1 MWe.

[5] Complete HT-HP performance map can be consulted in Annex II

## 7.2 ORC Performance Map[6]

As mentioned before, three options are given to the user to select the optimum outlet temperature for the preheater of the ORC (T_opt_LTWT). For options A and B the same ORC map is used, as the difference between them is the way to obtain T_opt_LTWT (by means of a correlation or introduced by the user). However, for option C, an extra condition has been set in the EES model (saturated state at the preheater outlet), so a different performance map is needed.

To ensure that only one of the options is selected, the variable **SF_option_selection** has been included. In case more than one option (or none of them) is selected, this variable will try to make a division by zero, leading to an error and stopping the simulation.

### ORC Map: Options A and B

To create this ORC map $T_{w\_in_{cond}}$, $\Delta T_{w\_cond}$ and $T_{LTWT}$ were used. In this case, the range of temperatures is also selected considering the working modes, but for the $T_{LTWT}$ the optimum value for these conditions is the input introduced in the map, so the range does not have to cover until the ambient temperature:

*Table 20: Temperature ranges for ORC performance map.*

| Variable | Values (°C) | | | | |
|---|---|---|---|---|---|
| $T_{w\_inlet\_cond}$ | 10 | 20 | 35 | 40 | 60 |
| $\Delta T_{w\_cond}$ | 2 | 5 | 10 | | |
| $T_{opt\_LTWT}$ | 40 | 55 | 70 | 85 | 100 |

Thus, the total number of points of this map is $5^2$*3= 75.

The inputs of the TRNSYS-CHEST model are similar to the HT-HP case:

- **T_w_in_cond_ORC_C**: Variable located in *CONTROL CARDS* that can be modified by the user according to the working mode that is to be simulated.
- **DT_w_cond_ORC_K:** Also modified by the user, in *CONTROL CARDS*.
- **T_opt_LTWT_C:** Optimum temperature that the flow through the preheater has to reach. This value is previously obtained using a correlation (OPTION A, section 6.3.1.1) or introduced by the user in CONTROL CARDS (OPTION B)

The outputs from this map used in the TRNSYS-CHEST model are:

- **P_q_sen_nom_ORC_MW**: Nominal sensible heat consumed from SH-TES by the ORC to have a nominal output power of 1 MWe.
- **P_q_lat_nom_ORC_MW:** Nominal latent heat consumed from the LH-TES by the ORC to have a nominal output power of 1 MWe.
- **P_q_cond_ORC_MW:** Nominal heat capacity of the ORC's condenser when having a nominal output power of 1MWe.

In this map there are some combination of points that cannot be calculated in the EES-ORC model because the second law of thermodynamics would be violated, as the temperature of the refrigerant entering the preheater is higher than the outlet temperature of the water,

[6] ORC performance maps can be consulted in Annex III and IV

$T_{LTWT}$. However, as TRNSYS type 42a needs a complete input file, these combinations have been included writing a zero for all the outputs. This does not affect the performance of the model when using option A, as it has been proved that these conditions are impossible to reach in the simulation. However, for option B, an adequate value of **T_opt_LTWT_user_option_B** should be selected so as to have a correct interpolation. For instance, for condenser temperatures higher than 35°C a T_opt_LTWT_user_option_B higher than 55°C should be selected. Otherwise, values of 0 will be used for the interpolation, as illustrated in Table 21.

*Table 21: Extract from the ORC performance map for options A and B.*

| $DTw\_cond_{ORC}$ [K] | $T\_opt_{LTWT}$ [C] | $T\_w\_cond_{ORC}$ [C] | $m\_w_{PH}$ [kg/s] | $Q\_SH\text{-}TES_{ORC}$ [MW] | $Q\_LH\text{-}TES_{ORC}$ [MW] | $Q\_cond_{ORC}$ [MW] | $\eta_{ORC}$ [-] |
|---|---|---|---|---|---|---|---|
| **2** | **40** | **35** | - | - | - | - | - |
| **2** | **55** | **35** | 12.810 | 4.20998 | 3.48063 | 6.65126 | 0.13 |

These outputs are obtained for an ORC providing 1 MWe of nominal net power. If this is not the actual case, the outputs are scaled according to the real state of the system (see Section 3.10).

**$T_{opt\_LTWT}$ Correlation (Option A)**

In this option T_opt_LTWT is obtained as the optimum value of the EES coupled model[7]. Thus, in the coupled model, $T_{LTWT}$ is optimized as a function of the other four variables $T_{w\_inlet\_evap}$, $\Delta T_{w\_evap}$, $T_{w\_inlet\_cond}$ and $\Delta T_{w\_cond}$. The name used for these variables in the TRNSYS-CHEST model are T_w_in_evap_HP, DT_w_evap_HP, T_w_in_cond_ORC and DT_w_cond_ORC respectively.

A first map using the coupled model has been made to obtain the values the tank temperatures should take. The values given to the variables are shown in Table 22:

*Table 22: Temperature ranges for source and sink.*

| Variable | Map | Values (°C) | | | | |
|---|---|---|---|---|---|---|
| **T_w_in_evap_HP** | HP | 40 | 55 | 70 | 85 | 100 |
| **DT_w_evap_HP** | HP | 2 | 5 | 7 | | |
| **T_w_in_cond_ORC** | ORC | 10 | 20 | 35 | 40 | 60 |
| **DT_w_cond_HP** | ORC | 2 | 5 | 10 | | |

A correlation to obtain the optimum value of $T_{LTWT}$, ($T_{opt\_LTWT}$) as a function of T_w_in_evap_HP, DT_w_evap_HP, T_w_in_cond_ORC and DT_w_cond_ORC has been calculated using the software R.

The correlation employed for the OPTION A was obtained using results from the coupled model of the EES-CHEST system. T_opt_LTWT_C is calculated as a function of the variables T_w_in_evap_HP, DT_w_evap_HP, T_w_in_cond_ORC and DT_w_cond_ORC. To find the appropriate correlation, the software R was used.

[7] The coupled EES-CHEST model is an initial approach of the CHEST system where there is an ideal heat transfer in the TES system and all the heat produced by the HT-HP is immediately discharged in the ORC, assuming steady state conditions.

Results show that the most influential variable is T_w_in_cond_ORC and that the value of T_opt_LTWT_C increases with the increase of the other variables (38). The most suitable option found was a quadratic correlation with a maximum error of 1.3%:

$$\begin{aligned} \text{T\_opt\_LTWT\_C} = {} & 31.55 + 0.8614 * \text{T\_w\_in\_cond\_ORC} + 0.2117 \\ & * \text{T\_w\_in\_evap\_HP} + 0.8314 * \text{DT\_w\_cond\_ORC} - 0.2228 \\ & * \text{DT\_w\_evap\_HP} - 4.716 * 10^{-4} * \text{T\_w\_in\_cond\_ORC}^2 \\ & - 1.241 * 10^{-3} * \text{T\_w\_in\_evap\_HP}^2 - 4.548 * 10^{-4} \\ & * \text{T\_w\_in\_cond\_ORC} * \text{T\_w\_in\_evap\_HP} - 1.101 * 10^{-3} \\ & * \text{T\_w\_in\_cond\_ORC} * \text{DT\_w\_cond\_ORC} + 2.567 * 10^{-3} \\ & * \text{T\_w\_in\_evap\_HP} * \text{DT\_w\_evap\_HP} \end{aligned} \quad (38)$$

This correlation is implemented in the TRNSYS-CHEST model to obtain the optimum temperature the cold tank has to reach. This input is used for the ORC map when Option A is activated, as it is the optimum outlet temperature of the water in the preheater.

## 7.4 ORC Map: Option C

To create the ORC map for option C $T_{w_in_{cond}}$and $\Delta T_{w_cond}$have been used. In this case, the range of the temperatures is also selected considering the different working modes:

*Table 23: Temperature ranges of the ORC performance map.*

| Variable | Values (°C) | | | | |
|---|---|---|---|---|---|
| $T_{w\_in_{cond}}$ | 10 | 20 | 35 | 40 | 60 |
| $\Delta T_{w\_cond}$ | - | 2 | 5 | 10 | - |

Thus, the total number of points of this map is 5*3=15.

The inputs of the TRNSYS-CHEST model are similar to the HT-HP case:

- **T_w_in_cond_ORC_C**: Variable located in *CONTROL CARDS* that can be modified by the user according to the working mode.
- **DT_w_cond_ORC_K:** Also modified by the user, in *CONTROL CARDS*.

The outputs from this map used in the TRNSYS-CHEST model are:

- **P_q_sen_nom_ORC_MW**: Nominal sensible heat consumed from SH-TES by the ORC to have a nominal output power of 1 MWe.
- **P_q_lat_nom_ORC_MW:** Nominal latent heat consumed from LH-TES by the ORC to have a nominal output power of 1 MWe.
- **P_q_cond_ORC_MW:** Nominal heat capacity of the ORC's condenser when having a nominal output power of 1MWe.
- **T_opt_LTWT_C:** Optimum temperature the flow going through the preheater has to reach. This optimum value is obtained assuming that the outlet of the preheater in the ORC is always in saturated state.

These outputs are obtained for an ORC providing 1 MWe of nominal power in the expander. If this is not the actual case, the outputs are scaled according to the real state of the system.

# 8 Annex C

Based on the results presented in D2.1 [9], three different scenarios or design months have been defined, normalizing the generations and demands.

## 8.1 Summer Season

Available Energy Profiles:

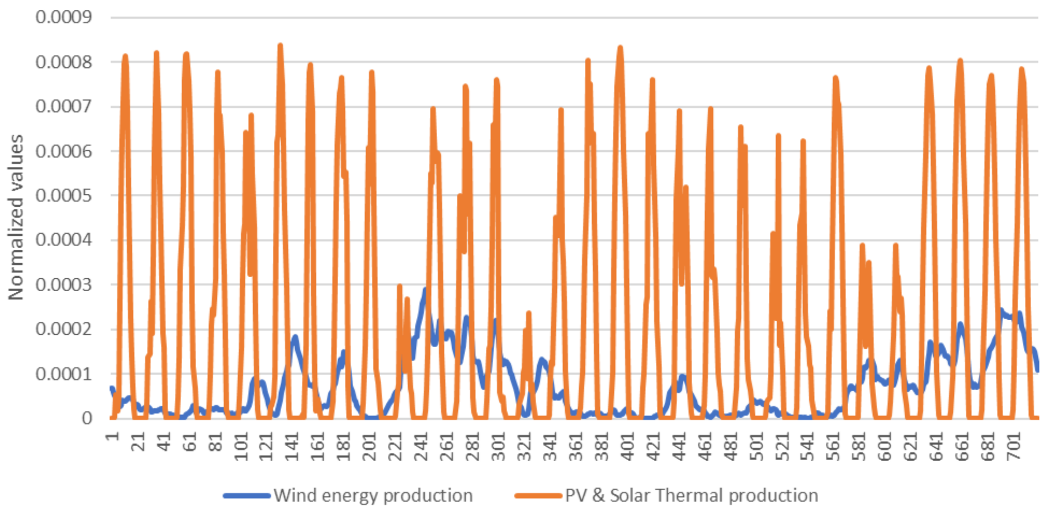


Figure 54: Available energy profile for summer season.

Demand profiles:

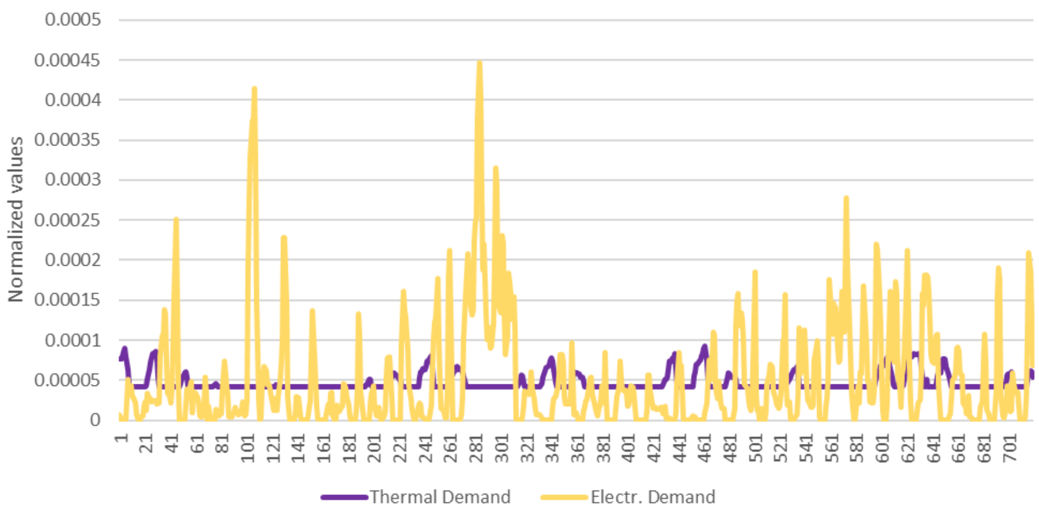


Figure 55: Demand profile for summer season.

## 8.2 Winter Season

Available Energy Profiles:

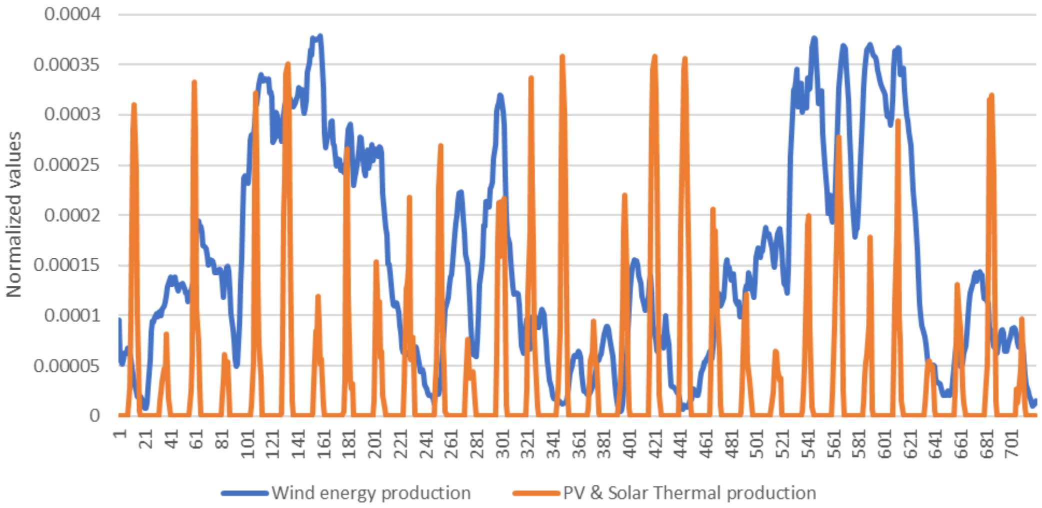


Figure 56: Available energy profile for winter season.

Demand profiles:

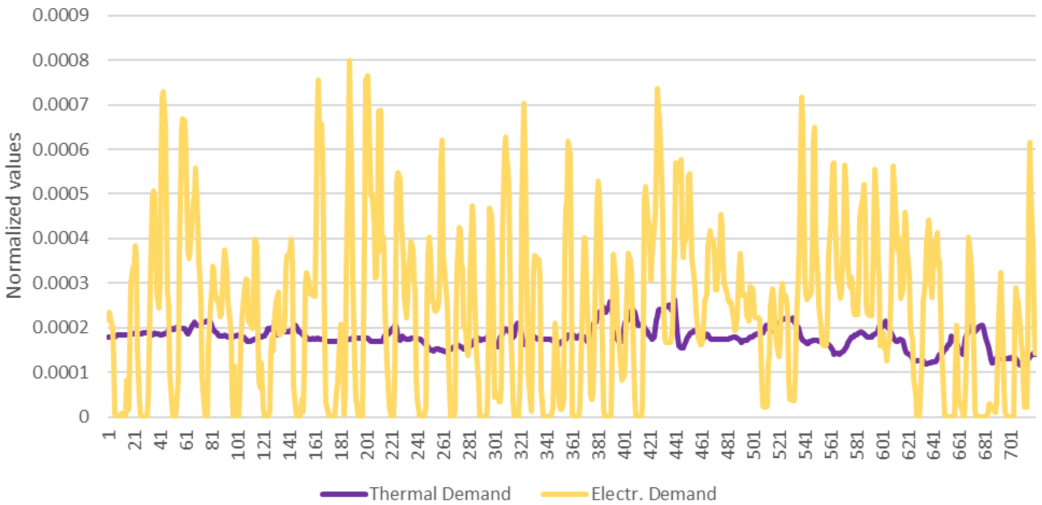


Figure 57: Demand profile for winter season.

## 8.3 Transitional period

Available Energy Profiles:

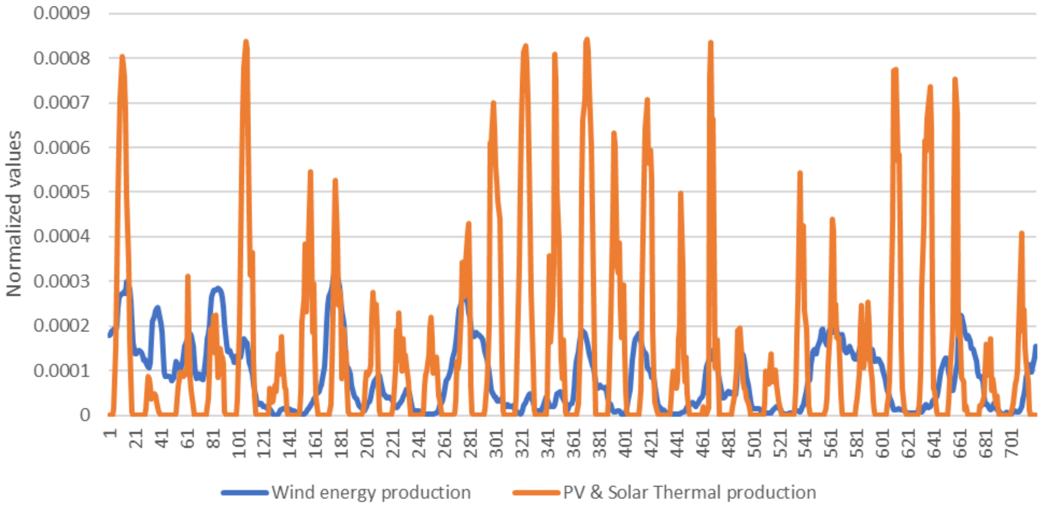


Figure 58: Available energy profile for transitional period.

Demand profiles:

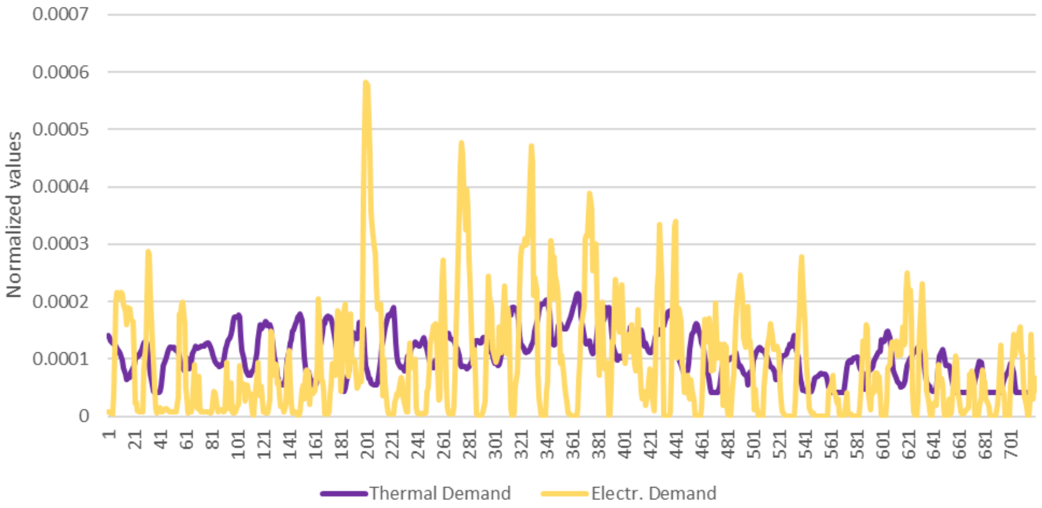


Figure 59: Demand profile for transitional period.

# References


[1] European Comission, “Annex I (part A). Research and innovation action: CHESTER,” no. 764042, 2018.

[2] L. Cecchinato, “Part load efficiency of packaged air-cooled water chillers with inverter driven scroll compressors,” *Energy Convers. Manag.*, vol. 51, no. 7, pp. 1500–1509, 2010.

[3] E. Comission, “Ecodesign Directive.” EU.

[4] CETIAT, “Part-load performance behavior of On-Off and variable capacity heat pumps.” Groundmed, Madrid, 2010.

[5] Danfoss, “The Turbocor Family of Compressors Model TT300, Danfoss TURBOCOR,” *Datasheet, www.turbocor.com, USA*, 2015.

[6] P. Fahlén, “Capacity control of heat pumps,” *Rehva*, no. October, pp. 28–31, 2012.

[7] Thermal Energy System Specialists, “Trnsys 18. Standard Component Library Overview,” vol. 3, 2017.

[8] Thermal Energy System Specialists, “Trnsys 18. Mathematical Reference,” vol. 4, 2017

[9] D2.1 Case studies: User Requirements and boundary conditions definition. CHESTER Deliverable. PlanEnergy