CHESTER

Compressed Heat Energy Storage for Energy from Renewable sources

Installation and commissioning of components and whole CHEST prototype

PROJECT	**CHESTER**
PROJECT NO.	**764042**
DELIVERABLE NO.	**5.2**
DOCUMENT VERSION	**1**
DOCUMENT PREPARATION DATE	**18.02.2022**
RESPONSIBILE PARTNER	**DLR**
DISSEMINATION LEVEL	**Public**

Type of Deliverable		
R	**Document, Report**	**x**
DEM	**Demonstrator, pilot, prototype**	
DEC	**Websites, patent fillings, videos, etc.**	
OTHER		
ETHICS	**Ethics requirements**	
ORDP	**Open Research Data Pilot**	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 764042.

EC Grant Agreement	No.764042
Project Acronym	CHESTER
Project Title	Compressed Heat Energy Storage for Energy from Renewable sources
Programme	HORIZON 2020
Start Date of Project	01-04-2018
Duration	48 Months

Financial/Administrative Coordinator	
Project Coordinator Organization Name	TECNALIA
Address	Parque Tecnológico de Bizkaia C/Astondo, Edificio 700 (Spain)
Phone Numbers	+34 946 430 850
E-mail Address	Maider.epelde@tecnalia.com
Project web-site	www.chester-project.eu

Version Management			
Filename		**D5.2: Installation and commissioning of components and whole CHEST prototype**	
Author(s)		**D. Bauer, A. Gutierrez, M. Johnson, T. Weller**	
Reviewed by		Felipe Trebilcock Kelly	
Approved by		Maider Epelde	
Revision No.	**Date**	**Author**	**Modification description**
RV 1	22/02/2022	FTK	Revision for final approval
RV 2			
RV 3			
RV 4			

Contents

List of Figures

List of Tables

Glossary, abbreviations and acronyms

CHEST	Compressed heat energy storage
CWN	Cooling water network
CWDN	Cooling water distribution network
HT	High temperature
HTF	Heat transfer fluid
HTHP	High temperature heat pump
LH	Latent heat
ORC	Organic Rankine Cycle
PCM	Phase change material
SH	Sensible heat
TES	Thermal energy storage
TESS	Thermal energy storage system

1. Introduction

1.1. Executive Summary

The installation and commissioning of the components and whole compressed thermal energy storage (CHEST) prototype has been completed. The high temperature thermal energy storage system (HT-TESS), the organic Rankine cycle (ORC) and the high temperature heat pump (HTHP) were tested individually (as reported in the deliverables D3.7, D3.8 and D3.6) and delivered to the laboratory (the HT-TESS was tested at this laboratory), installed and commissioned there.

1.2. Purpose and Scope

The objective of Task 5.2 is to install the components of the whole CHEST system and combine them to one laboratory system, making the testing of this novel system as a whole possible. This deliverable includes the installation and commissioning of the components in the CHESTER laboratory prototype loop.

1.3. Methodology

For this deliverable, the installation began with the arrival of the HTHP and ORC components in the laboratory. From this point on, the systems were connected to each other both physically with piping as well as into the laboratory infrastructure and control system. Once systems were attached, a step-by-step commissioning process for each of the components was conducted, allowing for a commissioning of the system.

1.4. Structure of the document

This document is divided in four main sections. Section 2 describes the prototype system and the system boundaries of the separate components. Section 3 discusses the installation process of each of the components. Section 4 follows with the details of the commissioning of the components. Finally, section 5 presents a conclusion of these works.

1.5. Relations with other deliverables

This work package and deliverable is closely related to the previously conducted deliverables D3.2, D3.3 and D3.4 as well as D3.6, D3.7 and D3.8. These discuss first the design and then the testing of the components HTHP, HT-TESS and ORC. In addition, this deliverable is closely related to D5.1, discussing the preparation of the laboratory test site.

In following work, D5.2 is closely related to work that will be reported in D5.3. This is the testing of the CHEST laboratory system.

2. CHESTER laboratory prototype

2.1. General description

The CHESTER project aims to develop and test an innovative CHEST system to manage, store and deliver energy from different renewable energy sources by combining the electricity and heat sectors[1]. The goal of the CHESTER laboratory system is to experimentally prove the CHEST system, showing that it is possible to provide a flexible electricity and heat dispatchment with discontinuous energy input from renewable sources. A simplified flow diagram with the main components of the CHESTER system is shown in Figure 1.

The lab-scale system is designed for an electrical output power of 10 kWe and also combines the main CHEST system components HTHP, ORC and HT-TESS. In contrast to the CHESTER concept and a large-scale version of the system, the lab-scale system is connected to a temperature-controlled heat source and -sink instead of a smart district heating network.

The HTHP upgrades heat from the low temperature source to a higher temperature that exceeds the melting temperature of the phase change material (PCM) used in the HT-TESS. In the case of the CHESTER laboratory prototypes, the temperatures go from 70 °C to 90 °C (low heat source temperature) to 135 °C to 138 °C (high heat source temperature), and the melting temperature of the PCM is 133 °C. When the system dispatches energy, the HT-TESS is discharged to power the ORC system in order to generate vapor at 128 °C and 20-24 bar and thereby generate electricity.

The heat source consists of an electric flow heater with a power rating of 100 kW, which is connected to the evaporator of the HTHP via a water circuit. The water temperature can be controlled by a three-way valve. Thus, in charging mode, the evaporator can be supplied with hot water in a temperature range between 40-100 °C. At the ORC condenser, the thermal energy is dissipated to a cooling water network (CWN). The heat sink is controlled by a three-way valve, with which it is possible to regulate the cooling water during discharging down to 17 °C.

The full details of this system are described in the CHESTER deliverables D3.2 to D3.8.

[1] Chester Project "https://www.chester-project.eu/"

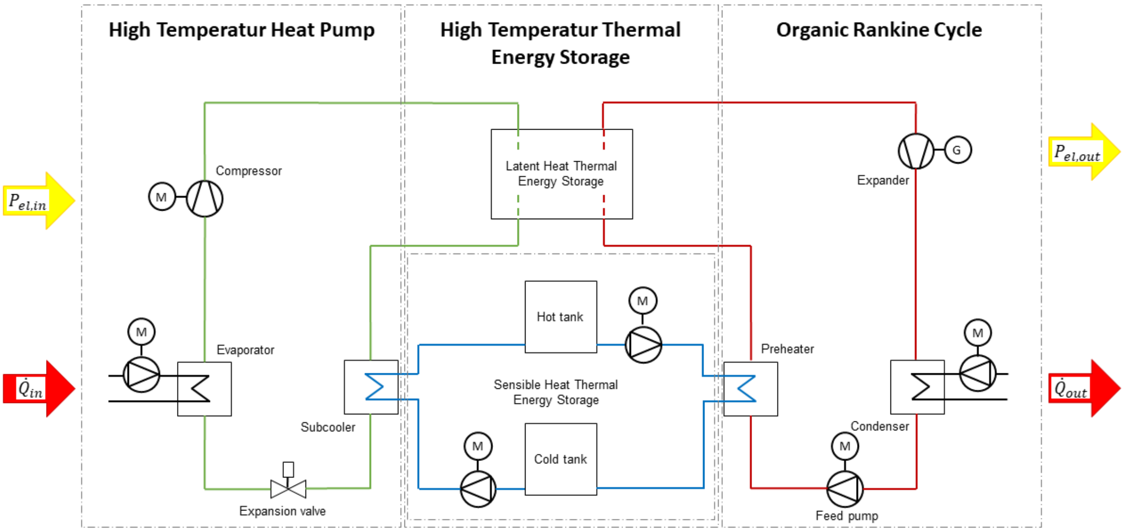

Figure 1: Simplified flow diagram of the laboratory CHEST system

2.2. Interfaces between the components

In the following subsection, each of the main components, specifically the connection points to the laboratory and the CHESTER laboratory prototype, are briefly described for a better understanding of the installation of the complete CHESTER laboratory prototype.

2.2.1. HT-TESS prototype

The HT-TESS is situated between the HTHP and the ORC, as shown schematically in Figure 1 and in the detailed piping and instrumentation diagram in the Annex. The HT-TESS absorbs heat provided by the HTHP during the charging mode, condensing the heat transfer fluid (HTF) in the process. During discharging, the HT-TESS evaporates the HTF, releasing the heat to the ORC system. The technical specifications and operating modes are described in detail in D3.3 and D3.7.

The HT-TESS is connected to both the HTHP and the ORC and the cooling water distribution network (CWDN). This is an intermediate water circuit through which the CHEST system components are connected to the cooling water network (CWN) (described in Section 3.2, subsection Heat sink). The HT-TESS is comprised of a latent heat thermal energy storage (LH-TES) and a sensible heat thermal energy storage system (SH-TESS), in order to provide all functionalities necessary within this system. The HT-TESS is connected to the data acquisition and controls system and the actuators for the valves are electrically powered by the lab infrastructure.

Figure 2 shows the piping connections of the LH-TES to the HTHP and ORC, with Table 1 describing the tags in the figure. Figure 3 shows the piping connections of the SH-TESS to the HTHP, ORC and the CWDN, with Table 2 describing the tags in the figure.

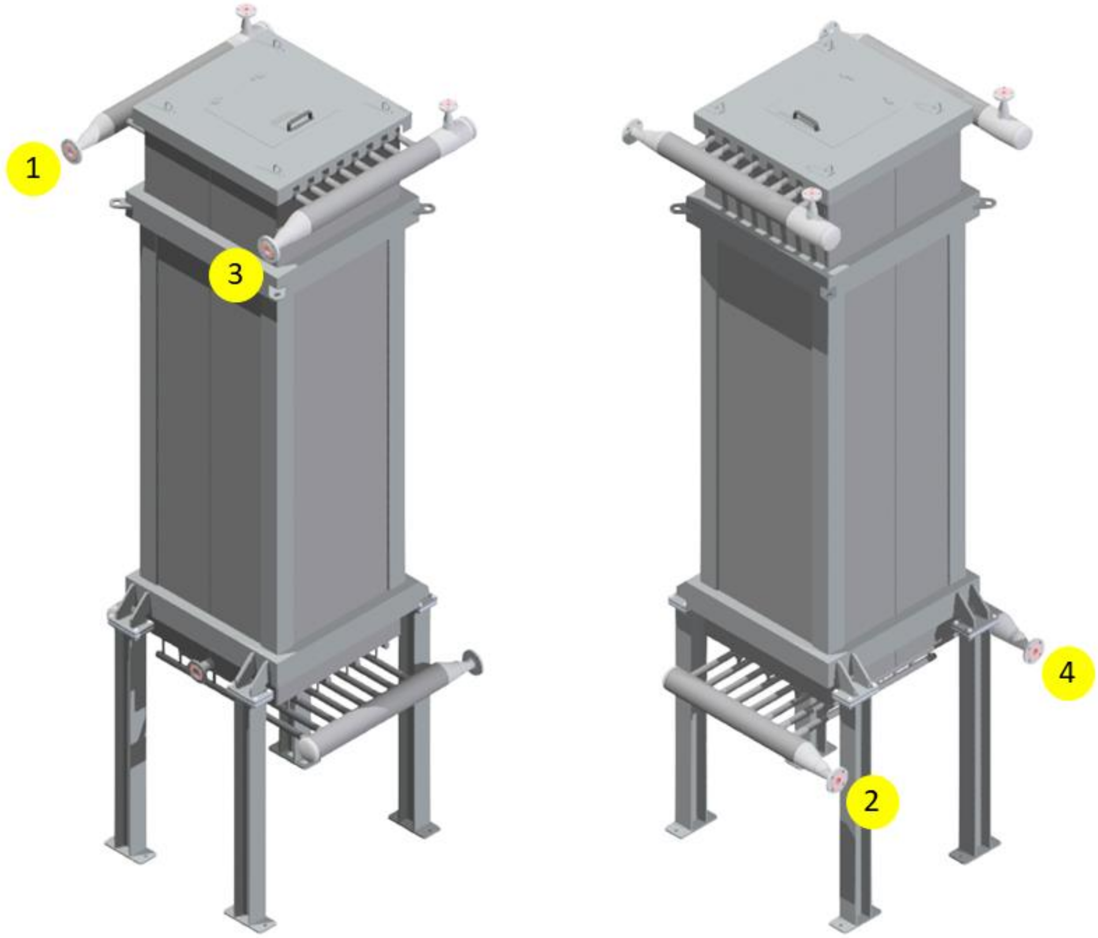

Figure 2: Schematic of the interfaces between LH-TES unit, HTHP and ORC; links in tabs described in Table 1

Table 1: Description of the interfaces between LH-TES unit, HTHP and ORC

Description	Tag number
Charging register inlet (from HTHP)	1
Charging register outlet (to HTHP)	2
Discharging register (to ORC)	3
Discharging register (from ORC)	4

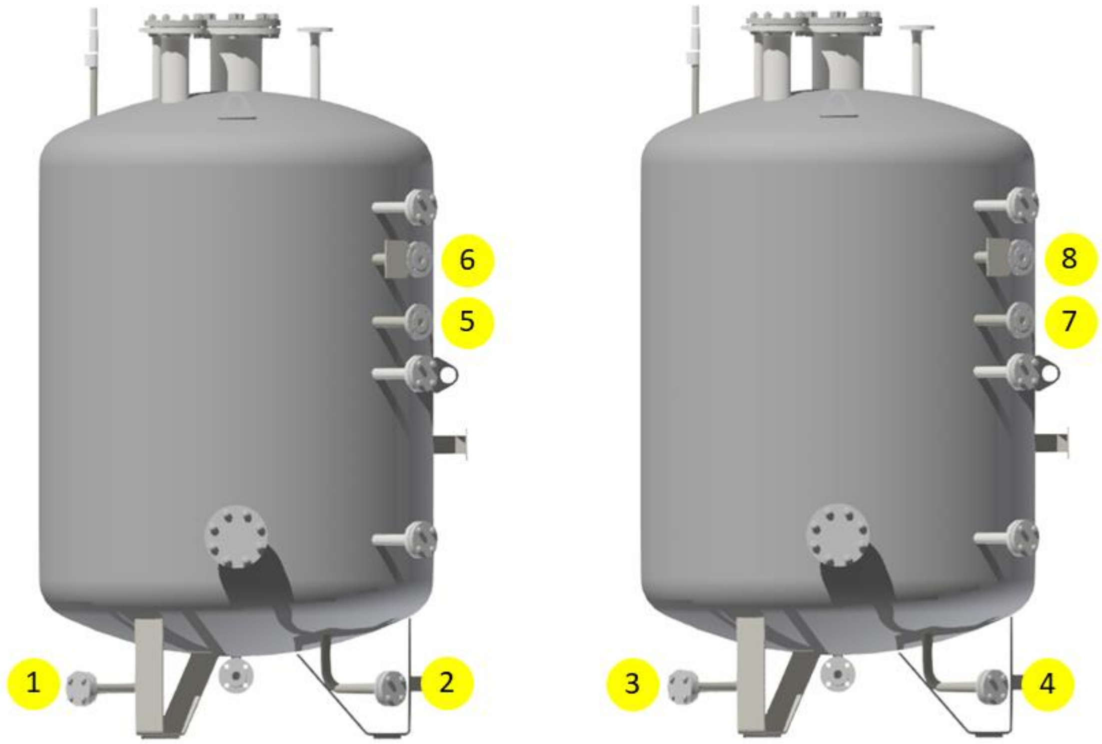

Figure 3: Schematic of the interfaces between hot tank (left) and cold tank (right) of the SH-TESS, HTHP, ORC and CWDN; links in tabs described in Table 2

Table 2: Description of the interfaces between SH-TESS, HTHP, ORC and CWDN

Description	Tag number
Hot water outlet (to ORC preheater)	1
Hot water inlet (from HTHP subcooler)	2
Cold water inlet (from ORC preheater)	3
Cold water outlet (to HTHP subcooler)	4
Water inlet (from CWDN)	5
Water outlet (to CWDN)	6
Water inlet (from CWDN)	7
Water outlet (to CWDN)	8

2.2.2. ORC prototype

The ORC is connected to the HT-TESS, as shown schematically in Figure 1 and in the detailed P&ID in the Annex. The ORC absorbs heat provided by the HT-TESS during the discharging mode, by evaporating the HTF in the process and converting the thermal energy partially back to electricity. The technical specifications and operating modes are described in detail in D3.4 and D3.8.

The ORC is connected to the HT-TESS and the CWDN. Electrical interfaces are the laboratory feed-in point and a connection to local area network (LAN, internet) for remote control. Figure 4 shows the piping connections of the ORC, with Table 3 describing the tags in the figure. The safety valves of the ORC are connected to the exhaust line; in case of an excess pressure, the refrigerant will be exhausted out of the lab to the atmosphere.

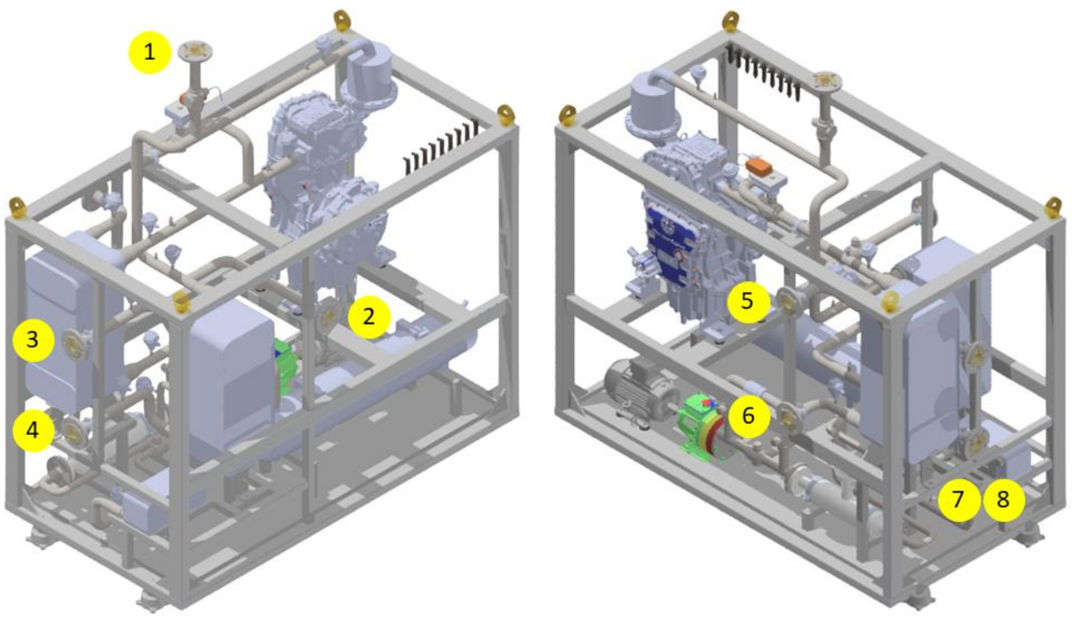

Figure 4: Schematic of the interfaces between ORC, HT-TESS and CWDN

Table 3: Description of the interfaces between ORC, HT-TESS and CWDN

Description	Tag number
Expander inlet (from LH-TES)	1
Preheater refrigerant outlet (to LH-TES)	2
Preheater water inlet (from SH-TESS)	3
Preheater water outlet (to SH-TESS)	4
Condenser water outlet (to CWDN)	5
Condenser water inlet (from CWDN)	6
Expander cooling and subcooler inlet (from CWDN)	7
Expander cooling and subcooler outlet (to CWDN)	8

2.2.3. HTHP prototype

The HTHP is connected to the HT-TESS, as shown schematically in Figure 1 and in the detailed P&ID in the Annex. The HTHP upgrades heat from the heat source by condensing the HTF. This charges the HT-TESS. The technical specifications and operating modes are described in detail in D3.2 and D3.6.

The HTHP is connected to the HT-TESS and the heat source. Electrical interfaces are the laboratory power supply and a connection to local area network (LAN, internet) for remote control. Figure 5 shows the piping connections of the HTHP, with Table 4 describing the tags in the figure. The safety valves of the HTHP are connected to the exhaust line; in case of an excess pressure, the refrigerant will be exhausted out of the lab to the atmosphere.

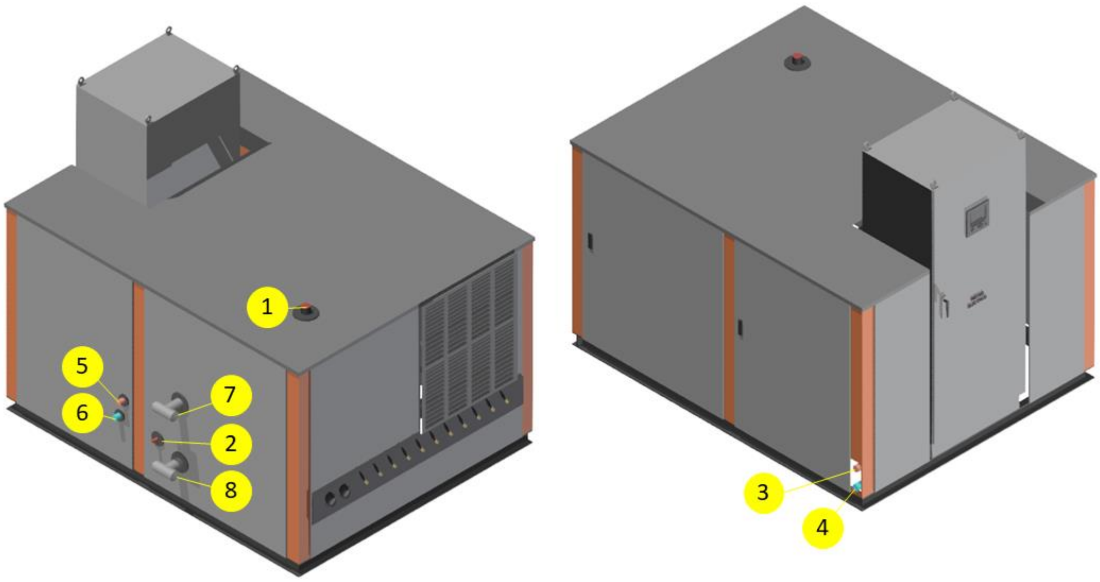

Figure 5: Schematic of the interfaces between HTHP, HT-TESS and heat source

Table 4: Description of the interfaces between HTHP, HT-TESS and heat source

Description	Tag number
Compressor refrigerant outlet (to LH-TES)	1
Liquid refrigerant inlet (from LH-TES)	2
Evaporator water inlet (from heat source)	3
Evaporator water outlet (to heat source)	4
Subcooler water outlet (to SH-TESS)	5
Subcooler water inlet (from SH-TESS)	6
Condenser water outlet[2]	7
Condenser water inlet[2]	8

3. Installation of the components

The installation of the CHEST system components must be performed in several steps. The LH-TES unit was tested in this laboratory in an earlier stage of the project. The HTHP, ORC and SH-TESS tanks could only be brought to the laboratory in a specific order due to limitations in space. A detailed description of these steps is given in the following section.

3.1. Final system layout

As a first step, the final CHEST laboratory prototype system layout was determined based on an analysis of different arrangements, considering the as-built dimensions of the HTHP, ORC and HT-TESS prototypes and the available laboratory space as well as the laboratory system connections (electricity, cooling water, etc.). The most suitable system layout derived from the analysis is shown in Figure 6.

[2] The condenser was used instead of the LH-TES unit during the individual prototype tests in the laboratory at Tecnalia.

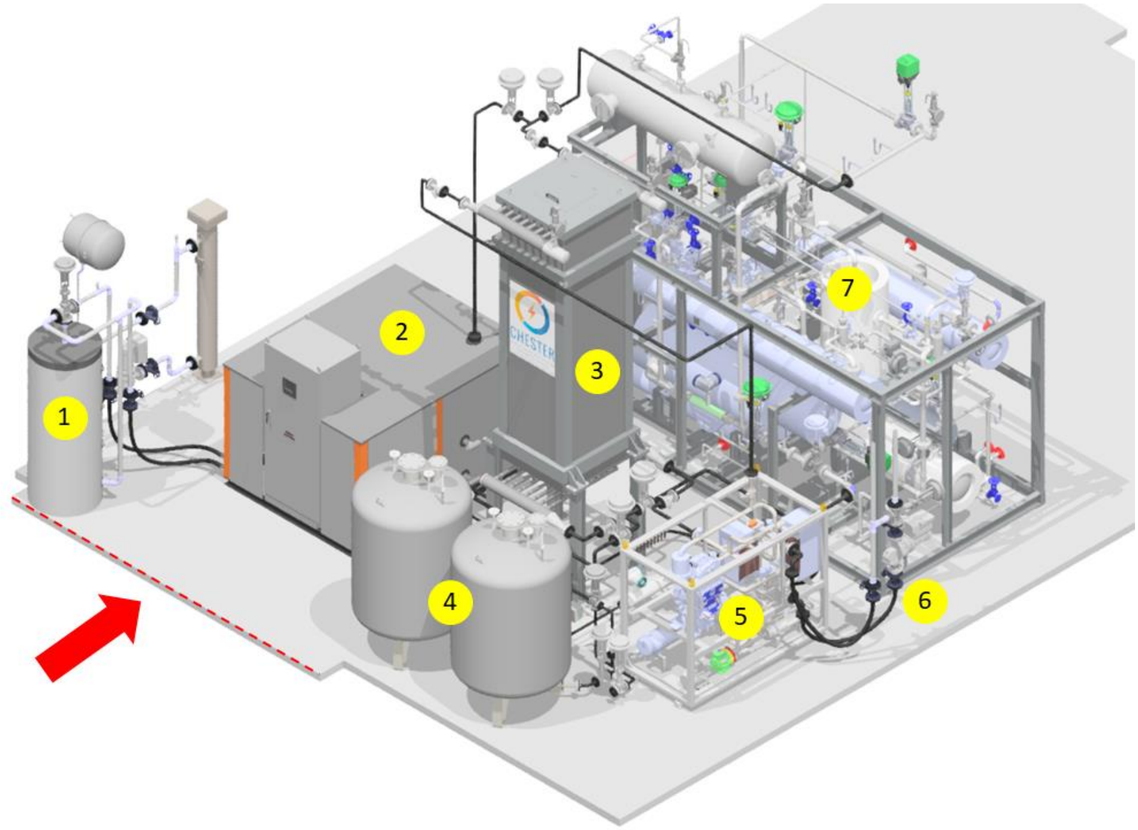

Figure 6: Final layout of the laboratory CHEST system showing pipe connections, main entrance to lab shown with the red arrow and red dotted line

The temperature-controlled heat source (1) on the left side is connected to the evaporator of the HTHP (2). In the center of the test rig is the HT-TESS comprising of the LH-TES unit (3) and the SH-TESS (4). The charging register of the LH-TES unit is connected to the HTHP and to a steam generator test rig for organic fluids (7), which was used during the storage tests and is used for initial conditioning of the system. Detailed information on the storage tests can be found in deliverable D3.7. The discharging register of the LH-TES unit is connected to the ORC (5). The tanks of SH-TESS are integrated between the subcooler of the HTHP and the preheater of the ORC. The connection between the condenser of the ORC and the cooling water distribution and thereby to the heat sink (6) is shown on the right side of the figure. A floor plan of the laboratory with the main components of the CHEST system and its dimensions is shown in Figure 7.

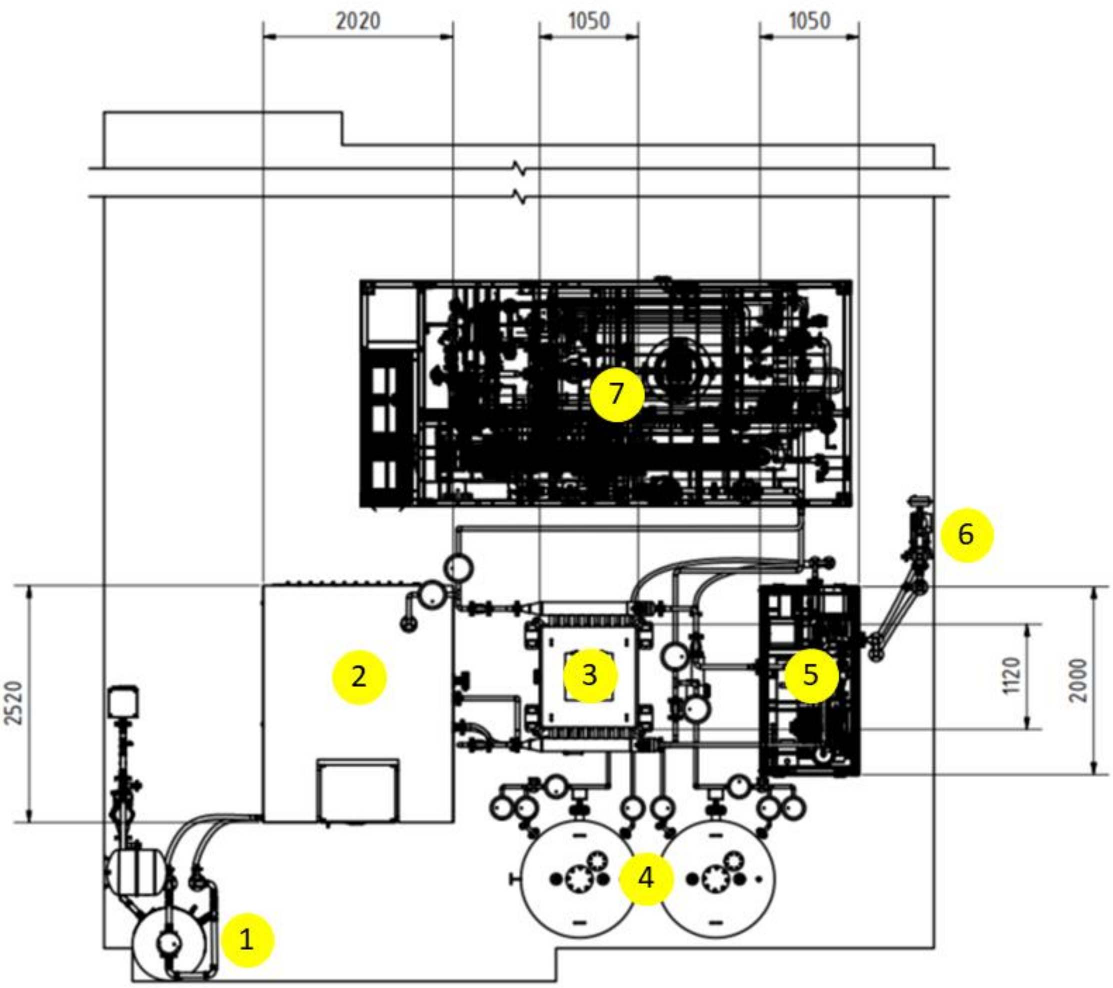

Figure 7: Laboratory floor plan with the main CHEST system components

3.2. Laboratory and system infrastructure

Prior to the integration of the main CHEST system components HTHP, ORC and HT-TESS, laboratory infrastructure such as heat source, cooling water supply and steam generator for organic fluids was installed. Detailed information on the design and control strategies of the laboratory infrastructure components can be found in deliverable D5.1.

Heat source

The temperature-controlled heat source (Figure 6/Figure 7 (1)) provides hot water to the evaporator of the HTHP (Figure 6/Figure 7 (2)). It consists of an electric flow heater with a power output range of 1-100 kW_{th}, a buffer tank used as a hydraulic separator, a primary and secondary circuit pump and a three-way mixing valve. A simplified schematic of the heat source is shown in Figure 8.

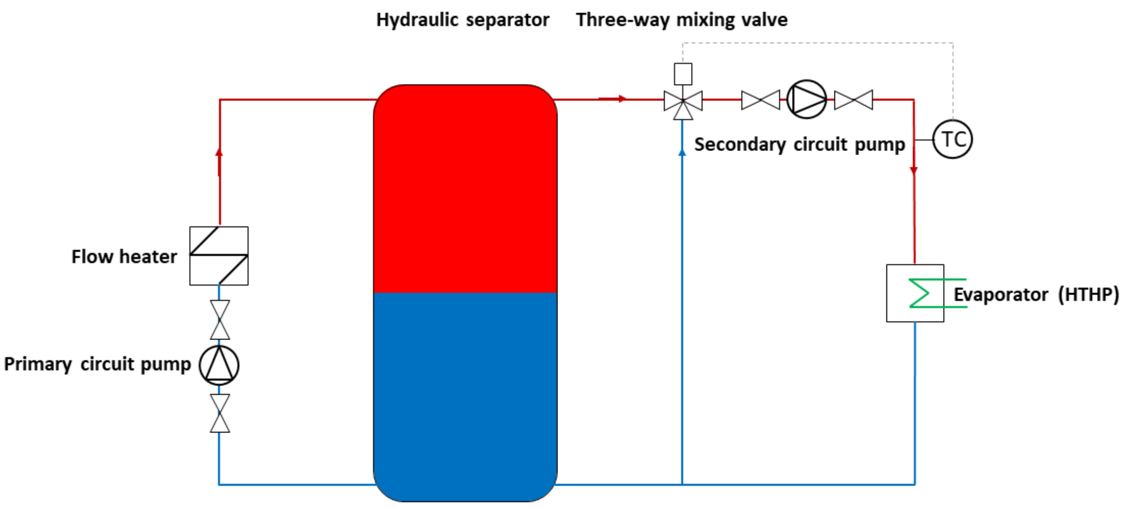

Figure 8: Simplified schematic of the temperature-controlled heat source

In operating mode, water is heated by the electric flow heater and circulated by means of the primary circuit pump between the flow heater and the hydraulic separator. With the secondary circuit pump, hot water and thereby thermal energy is fed to the evaporator of the HTHP. The water temperature is controlled by the three-way mixing and can be varied between 40 and 100 °C depending on the desired set-point. Safety equipment such as safety valve and pressure expansion vessels were installed in accordance with DIN EN 12828. An overview of the technical specifications is given in Table 5.

Table 5: Technical specifications of the temperature-controlled heat source

Description	Unit	Value
Heat source outlet temperature	°C	40-100
Thermal output	kW	1-100
Temperature difference between evap. inlet and outlet	K	5
Nominal pressure	PN	6

Figure 9 shows the final setup of the heat source in the laboratory. After the installation, the system was filled with softened water according to VDI2035 and insulated to minimize thermal losses to the environment.

Figure 9: Setup of temperature-controlled heat source in the laboratory

Heat sink

The laboratory CHEST system is connected to the DLR CWN via an intermediate water circuit, which connects to the ORC and the SH-TESS. This is shown in a simplified schematic in Figure 10.

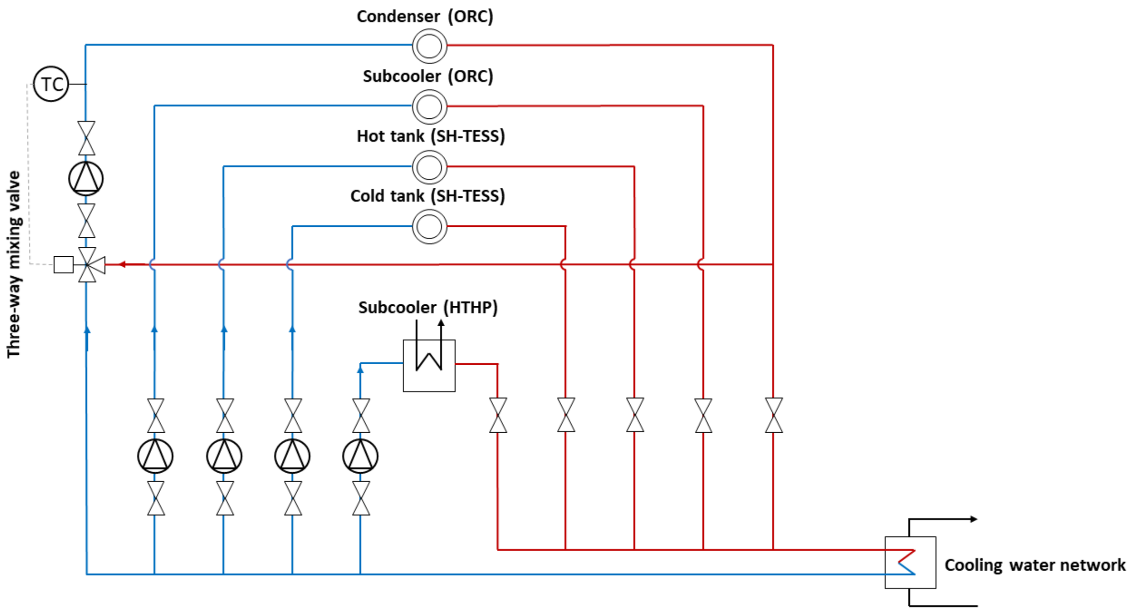

Figure 10: Simplified schematic of the CWDN (heat sink)

By means of various sub-circuits, the components of the laboratory system are supplied with cooling water as described below. These sub-circuits together build the CWDN, which is a closed-loop cooling water circuit separating the CHESTER system from the DLR CWN via a heat exchanger.

Condenser (ORC):

With this circuit, the thermal energy from the condenser is dissipated to the CWDN.

Subcooler (ORC):

The subcooler is used to achieve a defined condition at the inlet of the refrigerant pump and to prevent damage due to cavitation. In addition, this circuit is used to cool the expander motor during operation. Further information can be found in deliverable D3.4.

Hot tank and cold tank (SH-TESS):

Both tanks of the SH-TESS are equipped with internal heat exchangers, allowing the water temperature to be adjusted between experiments if necessary. In order to cool down each tank independently, two separate cooling water sub-circuits are installed.

Subcooler (HTHP):

For charging the LH-TES with the HTHP when the SH-TESS is fully charged, the water circuit of the SH-TESS is connected to the CWDN via a bypass. This allows for dissipation of the thermal energy from the subcooler. Since the water temperature in the SH-TESS water circuit can reach temperatures over 100 °C, this water circuit is separated from the CWDN by an additional heat exchanger.

During operation, the flow temperature supplied to the cooling water circuits from the CWN is approximately 17 °C. The ORC condenser circuit is equipped with a three-way mixing valve and a speed-controlled pump, which allows both the inlet temperature and the mass flow to be controlled. For all other circuits, constant mass flow rates are needed, which can be adjusted via manual flow regulators. Safety equipment such as safety valve and pressure expansion vessels were installed in accordance with DIN EN 12828. An overview of the technical specifications is given in Table 6.

Table 6: Technical specifications of the individual cooling water circuits

Description	Unit	Value
Condenser (ORC) inlet temperature	°C	20-50
Thermal output	kW	100
Temperature difference between in- and outlet	K	5
Subcooler (ORC) inlet temperature	°C	17
Thermal output	kW	4-12
Temperature difference between in- and outlet	K	5
Hot and cold tank HEX (SH-TESS) inlet temperature	°C	17
Thermal output (respectively)	kW	15
Temperature difference between in- and outlet	K	5
Subcooler (HTHP) inlet temperature	°C	17
Thermal output (respectively)	kW	50
Temperature difference between in- and outlet	K	5
Nominal pressure (whole intermediate circuit)	PN	6

Figure 11 shows the cooling water distribution in the laboratory. After the installation, the system was filled with softened water according to VDI2035 and insulated to minimize thermal losses to the environment and to avoid condensation on the tube surface.

Figure 11: Setup of cooling water distribution from the CWN in the laboratory

Steam generator

For the testing of the LH-TES, a stand-alone steam generator test rig was installed, which is designed for the evaporation and condensation of organic fluid at different pressures and mass flow rates. The final setup, the control modes and the integration of the steam generator test rig into the laboratory CHEST system is described in detail in deliverable D3.7.

Data acquisition and control

All data generated by the measurement instruments are logged in data acquisition systems and thus available for experimental analysis in Task 5.3. Each prototype has an individual control system consisting of a programmable logic controller (PLC) and a personal computer (PC). All internal processes during operation of the HTHP, ORC and HT-TESS are controlled via the respective PLC and visualized via the PC. In addition to HT-TESS, the system infrastructure is also controlled via the laboratory control system. Detailed information on system architecture, process variables and control loops of the individual control systems can be found in the deliverables D3.6, D3.8 and D5.1.

3.3. Installation of the HT-TESS

The installation of the HT-TESS was done in two steps, because as mentioned above, the LH-TES unit was tested and characterized in a first step before integration with the overall CHEST laboratory prototype system.

In a second step, the SH-TESS system was installed after the ORC and HTHP were in place, as the water circuit of the storage system is directly connected to the preheater (ORC) and the subcooler (HTHP).

3.3.1. LH-TES installation

The LH-TES was welded and pressure tested at the manufacturing facility and transported via truck to the DLR laboratory. Due to its height of more than 4.5 m, the LH-TES unit had to be brought into the laboratory in a horizontal position. The storage was then erected at the designated place and connected to the laboratory floor with one fix point bolt and three variable point bolts. The pipes between the LH-TES and the steam generator test rig were installed. The thermocouples in the LH-TES were coupled to the data acquisition system.

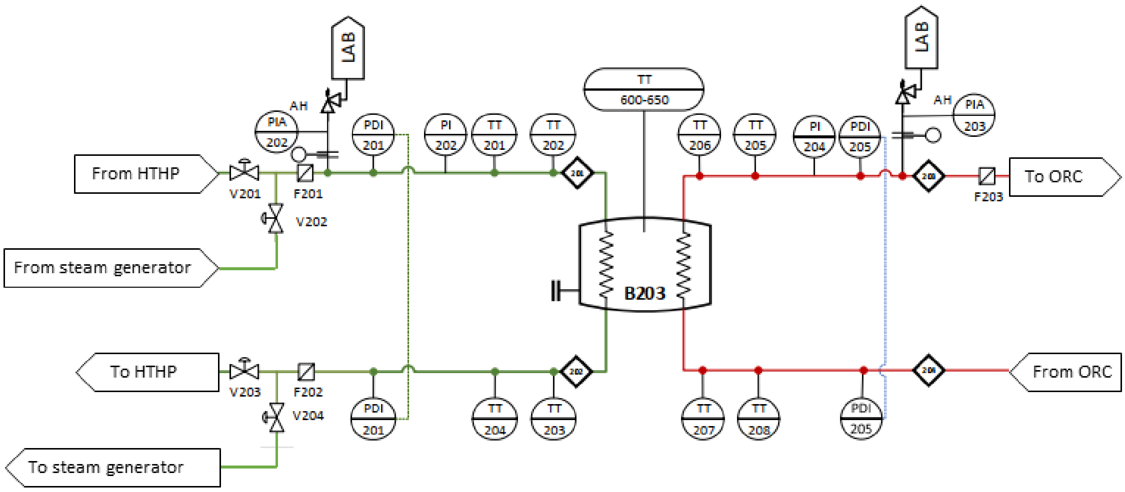

Figure 12: Integration of the LH-TES unit into the laboratory CHEST system. The charging register of the dual-tube heat exchanger is connected to the HTHP and the steam generator test rig (green) and the discharging register to the ORC (red)

The integration of the LH-TES unit into the CHEST laboratory system as well as the positions of the measurement equipment are shown in Figure 12. As described in deliverable D3.2 and D3.7, the LH-TES unit B203 is equipped with a dual-tube heat exchanger immersed in the PCM volume of the storage.

The steam generator together with the HTHP is connected to the charging register on the left side (green). By means of the control valves V201, V202, V203 and V204, the refrigerant flow can be changed and therefore the storage can be charged either by the HTHP or by the steam generator test rig. The latter, however, is mainly used during dedicated individual storage tests or, in CHESTER laboratory prototype testing, for bringing the PCM in the LH-TES to a desired temperature within the experimental campaign in Task 5.3.

The refrigerant loop of the ORC is connected to the discharging register on the right side (red). To ensure a proper and safe operation, filters F201-F203 and safety valves with bursting discs are installed directly at the connections to the header outlet of the LH-TES. After the installation of the pipes, pressure tests were conducted, the whole component was insulated and all electrical components (pumps, sensors, actuators, etc.) were connected to the lab control system.

Since the LH-TES unit is a passive component, there are no control circuits that actively actuate/regulate the storage during operation. The behavior of the storage mainly depends on the charging and discharging parameters (pressure, temperature, mass flow) of the HTHP and ORC as well as on the resulting heat transfer between the refrigerant and the PCM. In standby mode, the thermal loses to the environment are reduced by an electrical trace heater; this is mounted between the LH-TES insulation layer and the storage walls. The temperature of the trace heating is controlled by the laboratory control system.

For the temperature measurements, PT100 were installed in the refrigerant circuits and multi-point thermocouples were mounted on specific positions in the PCM volume of storage during storage manufacturing. The pressure is measured at the inlet and outlet of each register using pressure sensors. For more information on the test setup of the LH-TES unit, shown in Figure 13, see deliverable D3.7.

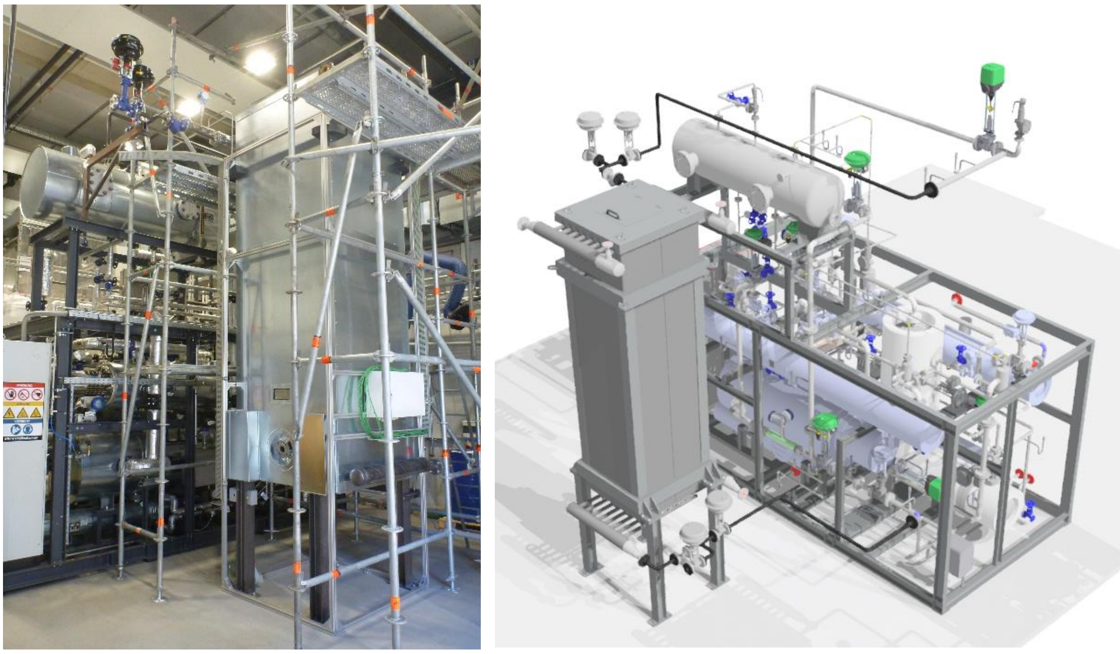

Figure 13: LH-TES connected to the steam generator in the laboratory at DLR site. Test setup during installation (left) and 3D-drawing showing the system layout and pipe connections (right)

3.3.2. SH-TESS installation

Figure 14 shows the P&ID integration of the SH-TESS in the laboratory CHEST system. On the charging side (blue lines, left), the cold tank B201 is connected to hot tank B202 via the subcooler W103 of the HTHP. In addition, this pipe section has a bypass to the CWN via heat exchanger W003. On the discharging side (blue line, right) the hot tank is connected to the cold tank via the preheater W301 of the ORC. Since both the subcooler and the preheater are internal components of the HTHP and the ORC prototypes, respectively, the water pipes are installed between the storage tanks and the interfaces, which are marked by the rhombic symbols. After the installation of the pipes, pressure tests were conducted, the whole component was insulated and all electrical components (pumps, sensors, actuators, etc.) were connected to the lab control system.

In order to adjust the water temperature as necessary, both tanks are equipped with immersion heaters W202 and W204 as well as the internal heat exchangers W201 and W203. The immersion heaters, with a power rating of 9 kWe, were mounted on a dedicated flange and electrically connected to the lab control system. The internal heat exchangers were connected to the CWN.

The pressure in the tanks is maintained by the nitrogen pressure control system PC206. It consists of two solenoid valves and the pressure sensor PI207. These components are installed on the upper flange of the hot tank and connected to the DLR nitrogen infrastructure and to the blowout line, together with the safety valves of the storage. In addition, a so-called communication line between the hot and the cold tank is installed to compensate pressure differences due to level changes during operation. The integration of pressurized water tanks and a nitrogen buffer for subcooling and preheating is a novel storage design, implemented here for the first time.

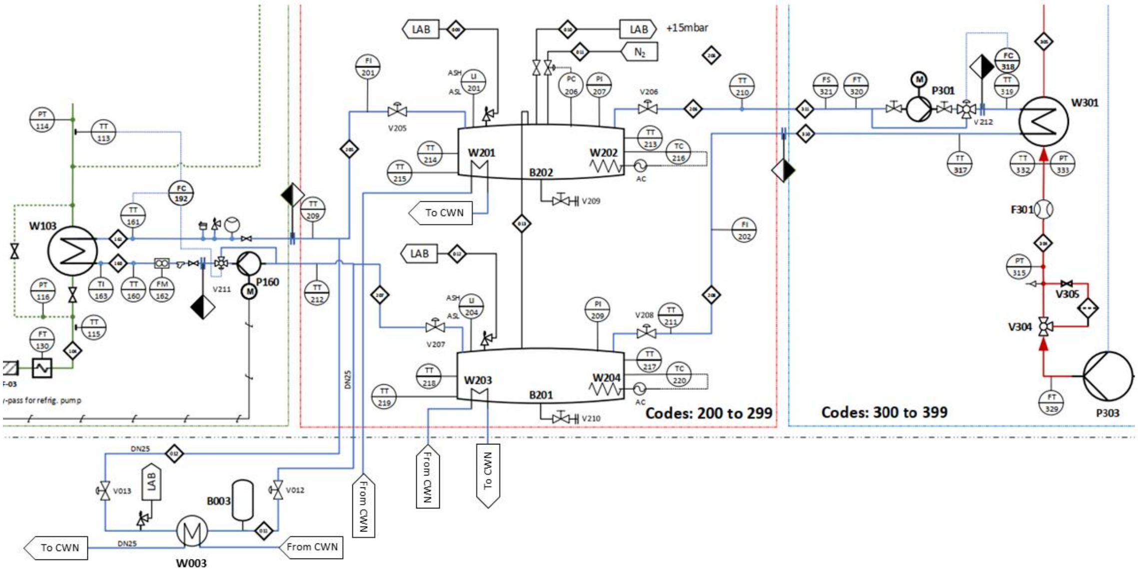

Figure 14: Integration of the SH-TESS into the laboratory CHEST system. Charging side (blue lines, left) is connected to the subcooler W103 of the HTHP and to the CWN; discharging side (blue lines, right) to the preheater W301 of the ORC

For the SH-TESS, the following control loops are implemented in the laboratory control system:

Subcooler (HTHP) control loop:

In order to achieve the highest possible temperature at the water outlet of the subcooler W103, the mass flow rate is controlled via the three-way valve V211 and the speed of pump P160. The aim is to achieve the smallest possible temperature difference between the refrigerant flow at the inlet and the water outlet of the subcooler, without decreasing the mass flow towards zero. The mass flow rate on the water side is measured by the Coriolis flow meter FI201.

A second operating mode of the subcooler control loop allows the SH-TESS to be bypassed via the W003 heat exchanger, so that thermal energy can be delivered directly to the CWN. This is needed when the maximum water level in the hot tank is reached before the LH-TES is fully charged by the HTHP.

Preheater control loop:

During operation of the ORC, the refrigerant should exit the preheater in a saturated state or slightly below the saturation temperature. This is achieved by varying the flow rate on the water side of W301. The water flow rate is controlled via the three-way valve V212 and the speed of pump P301. The mass flow rate on the water side is measured by the Coriolis flow meter FI202.

Nitrogen pressure control loop:

With the pressure control system, a constant pressure of 5 bar is maintained in SH-TESS tanks. The pressure is measured in both tanks by means of the sensors PI207 and PI209.

When the pressure drops, the inlet solenoid valve opens and nitrogen is supplied until the set-point is reached. When the pressure exceeds the set-point, the outlet solenoid valve opens and nitrogen is discharged through the blowout line. A hysteresis of ± 0.1 mbar prevents the valves from unwanted frequency switching.

Immersion heater control loop:

If required, both electric immersion heaters can be activated manually and independently of each other. The water in the tanks can be heated to a maximum temperature of 150 °C. The heating process is controlled by an internal temperature sensor. Once the setpoint value is achieved, the water temperature is maintained

Cooling water control loop:

In case the water in the tanks exceeds the desired temperature, each tank can be actively cooled via the internal heat exchanger, which is connected to the CWDN (described in Section 3.2, subsection Heat sink). For the cooling process, the corresponding pump is activated manually until the desired temperature is reached. The water temperature is measured by the PT100 sensors TT213-219.

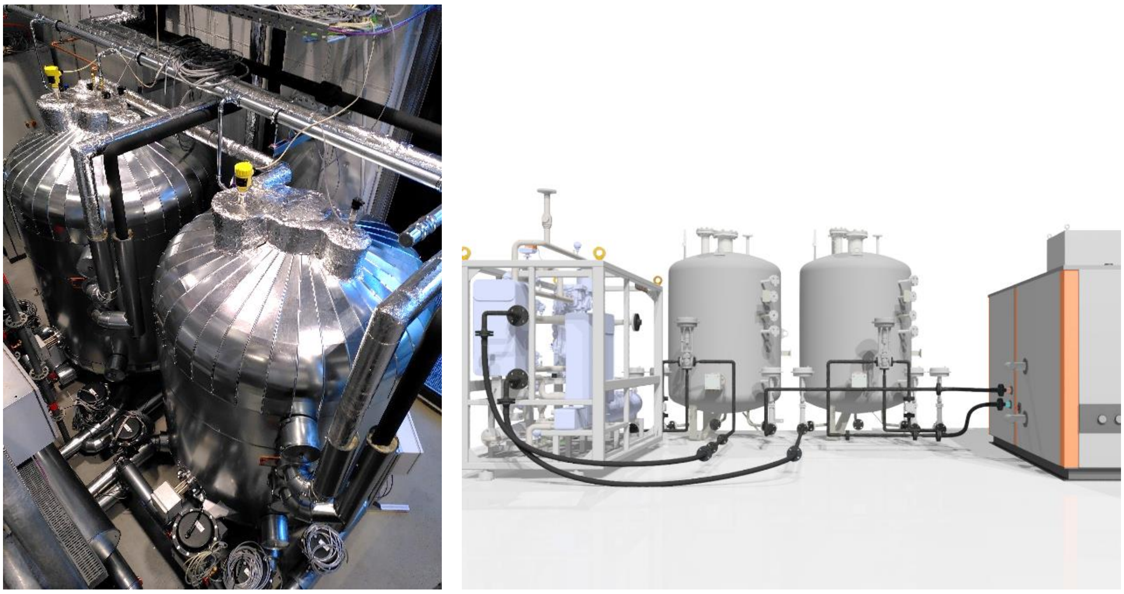

Figure 15: SH-TESS connected to the preheater of the ORC and the subcooler of the HTHP. Final laboratory arrangement (left) and 3D-drawing created for planning the system layout and pipe connections (right)

3.4. Installation of the ORC

The integration of the ORC into the CHEST laboratory system is shown in Figure 6 and Figure 16. The preheater W301, integrated into the ORC component, is connected to the water circuit of the SH-TESS. The discharging register of the LH-TES unit B203 is directly integrated into the refrigerant circuit by a welded pipe connection. Expander, subcooler as well as condenser (heat sink) are connected to the CWDN (see also section 3.2). Since the expander in the ORC is not internally decoupled from the pipe connections and the frame by vibration dampers, all connections between the ORC and the different components of the lab system, except those to the LH-TES, were carried out with hoses; this is to minimize the transmission of vibrations to the piping and thus to the whole test rig. The LH-TES is connected directly with steel pipes, as the combination of operating pressures and temperatures, the choice of refrigerant and the installation position pose a challenge for standard hose systems. In this case, the vibration is only absorbed by the pipe routing between the ORC and the LH-TES unit. Pressure tests and insulation of the pipes and hoses concluded the installation.

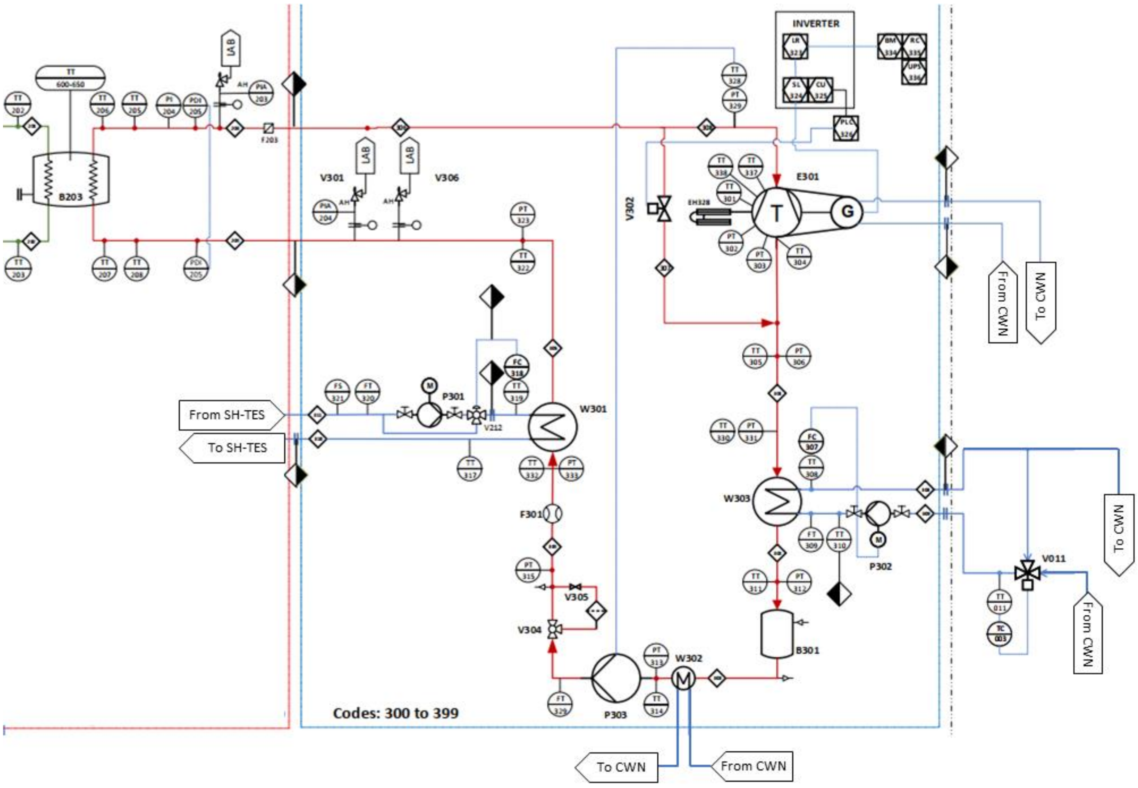

Figure 16: Integration of the ORC into the laboratory CHEST system. The preheater W301 is connected to the SH-TESS and the subcooler, the expander cooling loop and the condenser to the CWN. The LH-TES unit (used as the evaporator) is directly integrated into the refrigerant circuit (red)

A detailed description of the ORC control architecture, the internal control loops and strategies can be found in the deliverables D3.4 and D3.8. The final arrangement on the laboratory and the 3D-drawing created for planning the system layout and pipe connections is shown in Figure 17.

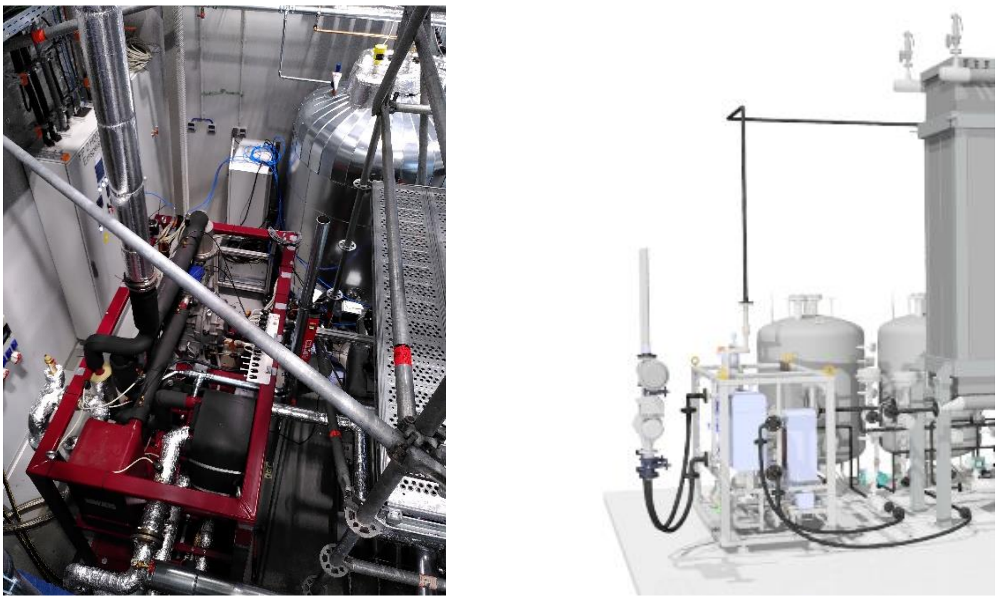

Figure 17: ORC integrated into the laboratory CHEST system. Final laboratory arrangement (left) and 3D-drawing, with the ORC prototype on the left, created for planning the system layout and pipe connections (right)

3.5. Installation of the HTHP

The integration of the HTHP into the CHEST laboratory system is shown in Figure 6 and Figure 18. The SH-TESS water circuit is connected to the subcooler W103, while the charging register of the LH-TES unit B203 is directly integrated into the HTHP's compressor discharge line (refrigerant circuit). The evaporator is connected to the heat source (see also section 3.2). In contrast to the expander in the ORC, the compressor of the HTHP is internally mounted on vibration dampers, so that the transmission of vibrations to the frame and the pipe connections is significantly lower. Nevertheless, the connections to the heat source and SH-TESS were made with hoses. Similar to the ORC circuit, the LH-TES is connected directly with steel pipes. Remaining vibrations should be absorbed by the pipe routing between the HTHP and the LH-TES unit. Pressure tests and insulation of the pipes and hoses concluded the installation of the HTHP.

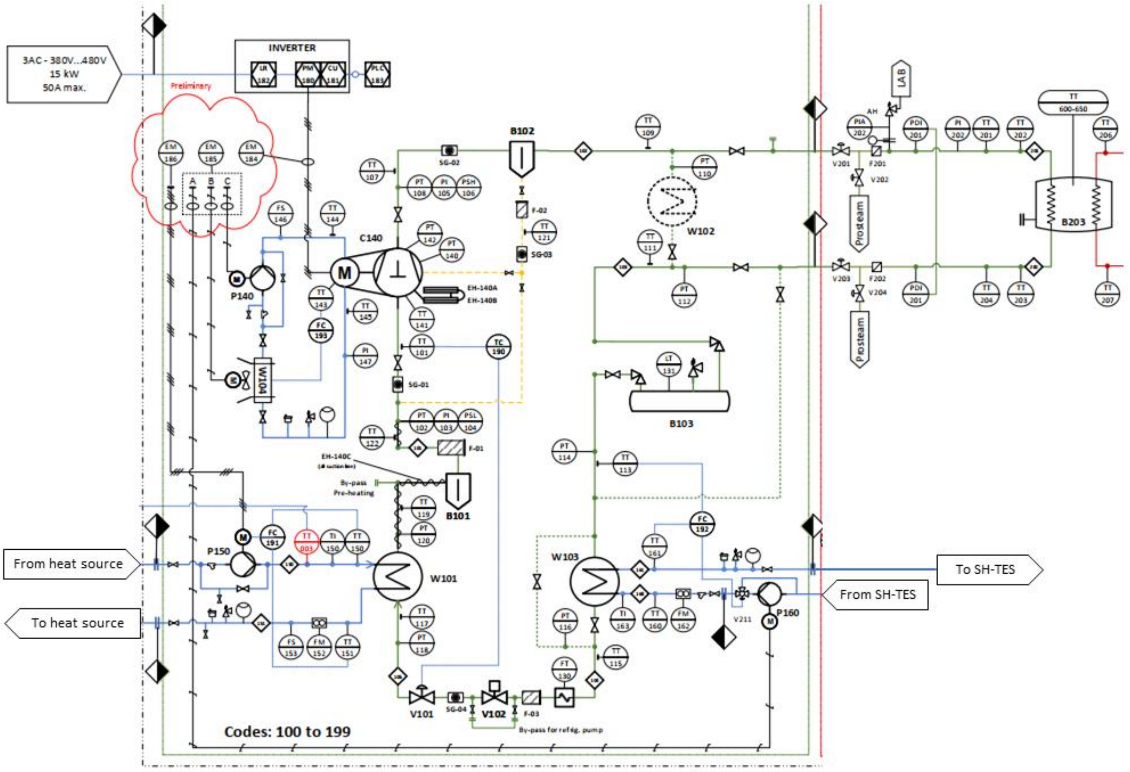

Figure 18: Integration of the HTHP into the laboratory CHEST system. The evaporator is connected to the heat source and the subcooler to the SH-TESS. The LH-TES unit (used as the condenser) is directly integrated into the refrigerant circuit (red)

A detailed description of the HTHP control architecture, the internal control loops and strategies can be found in the deliverables D3.2 and D3.6. The final arrangement in the laboratory and the 3D-drawing created for planning the system layout and pipe connections is shown in Figure 19.

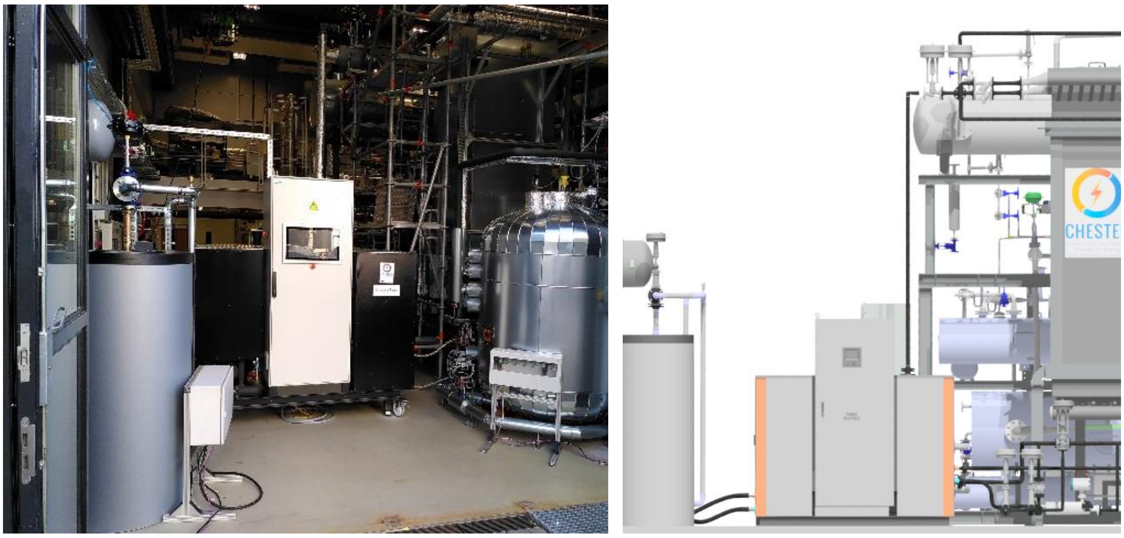

Figure 19: HTHP integrated into the laboratory CHEST system. Final arrangement (left) and 3D-drawing for planning system layout and pipe connections (right)

4. Commissioning of the CHEST prototype

4.1. General description

The commissioning of the laboratory CHEST system was carried out in several steps. In a first step, the individual components were prepared for the initial startup after transportation to this laboratory and installation in the CHEST laboratory system. This includes tasks such as in-situ pressure tests of the refrigerant circuits, filling of HTF, lubricant and storage medium, powering-up of control cabinets, etc. These tasks were summarized for the HTHP and ORC respectively by Tecnalia and UGent in so-called “setup task lists”, as, due to complications due to COVID-19 restrictions, these systems were installed in the laboratory in Stuttgart by DLR and not by the partners themselves. In a second step, ORC and HTHP were started and the operation with the HT-TESS in “manual mode” was tested for the first time with the respective partners.

The individual steps carried out are explained in the following sections.

4.2. Commissioning of the HT-TESS

The commissioning of the HT-TESS was separated into the commissioning of the two partial systems, LH-TES and SH-TESS. Since the LH-TES unit is a passive component, the commissioning process mainly comprises of the filling of PCM and a functional check of the measurement equipment. Both were carried out within the preparation of the test setup for the individual prototype tests in Task 3.2 and are described in detail in deliverable D3.7.

The SH-TES system, on the other hand, actively interacts with the subcooler of the HTHP and the preheater of the ORC during operation. Thus, the commissioning procedure includes, besides the filling with the storage medium, also a functional check of the control loops implemented in the laboratory control system. The steps carried out for the commissioning of the SH-TESS are described below.

Filling of storage medium:

Water is used as the storage medium in the SH-TESS. Since the temperatures in the storage exceed 60 °C, the filling water was treated in accordance with VDI 2035. This avoids efficiency losses due to limescale deposits in the heat exchangers and malfunctions caused by solid particles. By means of a water treatment system, the water hardness in the storage circuit is reduced to 0 °dH while the pH value is adjusted to approx. 8.5. The device used for filling the storage tanks with water is shown in Figure 20.

Figure 20: Device used for filling and flushing the SH-TESS, heat source and cooling water circuits with treated water

The device consists of a water tank with an internal pump circuit, which is connected to the storage circuit via hoses. During the filling process, tap water is fed into the device water tank and treated while it flows through the cartridge. A sensor determines the capacity of the cartridge based on the flow rate and the water composition and indicates when it needs to be exchanged. Depending on the operation mode, the device can be used for flushing or filling of closed water circuits.

The aim of the filling process is to deaerate the entire circuit and achieve the water levels in the tanks (marked in blue) required for commissioning of the HTHP, as shown in Figure 21. Therefore, the entire SH-TESS was first filled with nitrogen by means of the pressure control system, while the air was released with corresponding drain valves. Then, the cold tank was filled via the preheater circuit until the maximum water level was reached.

In a next step, the water circuit between the subcooler, CWDN and the SH-TESS tanks, as indicated by the blue dashed line, was filled and flushed until all remaining gas was removed.

In a final step, water was filled into the hot tank via the drain valve at the bottom of the tank, marked by the green dashed arrow, until the minimum water level was reached, and the volume above the water levels was filled with nitrogen and pressurized to 5 bar by the pressure control system.

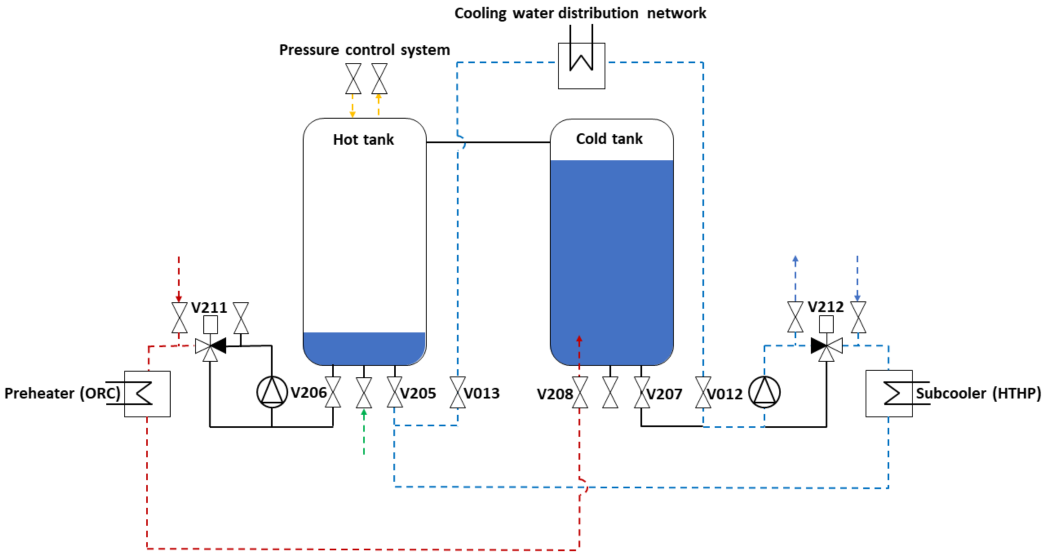

Figure 21: Simplified schematic of the SH-TESS water circuit. The dashed lines indicate the flushing paths during the filling process

Functional check of control loops (described in section 3.3.2):

During this check, the function of valve actuators and pumps according to predefined step-chains as well as measuring instruments installed in the storage system were tested. Therefore, the water was heated and cooled and pumped between the tanks while controlling the mass flow rates. In addition, the level sensors were adapted to the storage tank dimensions and the control loop of the pressure control system was optimized.

4.3. Commissioning of the ORC

The ORC prototype was prepared for commissioning according to a setup task list provided by UGent. The tasks required for commissioning are presented in Table 7 and described below.

Table 7: Setup task list for the ORC prototype

Category	Task No.	Task
1. Arrival	1.1	Unboxing and transport to the final position in the lab
2. Preliminary check	2.1	Visual check of internal piping and components
	2.2	Check of control and chopper cabinet
3. Water circuits	3.1	Flushing of condenser and preheater
	3.2	Connection of water pipes
	3.3	Filling of water circuits and leak test
4. Refrigerant circuit	4.1	Check of nitrogen pressure
	4.2	Connection between ORC and LH-TES
	4.3	Filling of expander with the lubricant
	4.4	Charge of refrigerant and leak test
5. Wiring	5.1	Wiring between ORC and control cabinet
	5.2	Power up the control cabinet
6. Operational	6.1	Check operation of water pumps and valves
	6.2	Check operation of expander
	6.3	Check operation of ORC bypass valve
	6.4	Check operation of ORC refrigerant pump
7. Startup	7.1	ORC test run with preheater only
	7.2	ORC test run with full HT-TESS

Task 1.1 – Unboxing and transport to the final position in the lab:

After delivery, the ORC prototype was transported to the designated location in the laboratory. Then both the plastic wrapping and the plexiglass covering, which were attached as transport protection, were removed. In order to reduce the vibrations, rubber dampers were mounted under the adjustable stands and the prototype was aligned. Figure 22 shows the ORC prototype at its final position in the laboratory and one of the adjustable stands with a mounted rubber damper.

Figure 22: ORC prototype at its final position in the laboratory (left) and stand with mounted rubber dampers (right)

Task 2.1 – Visual check of internal piping and components:

The visual check serves to identify damages that may have occurred during transport. Therefore, the interior of the prototype was inspected for loose components, missing insulation, bent or broken sensors, cut cables, etc. The visual inspection was documented with a video and photos accordingly. During the check, no major damages were detected.

Task 2.2 – Check of control/power cabinet:

The control and chopper cabinet[3] were assembled and a visual check for potential transport damages conducted. Both cabinets were inspected for loose connections, detached components, damaged cables, etc. The visual inspection was documented with photos. During the check, no major damages were detected.

Task 3.1 – Flushing of condenser and preheater:

During the individual prototype test in the laboratory of UGent, a water-glycol mixture as well as thermal oil were used as heat transfer media for the heat source and heat sink. To remove possible residues or corrosion deposits from the heat exchangers and thus avoid contamination of the SH-TESS and the CWDN, both the preheater and the condenser were flushed with a solvent (only the thermal oil circuit) and clean water.

Task 3.2 – Connection of water pipes:

As described in section 3.4, the condenser, expander cooling and subcooler were connected with hoses to the CWDN while the preheater was connected to the SH-TESS water circuit. The hose connections between the ORC prototype and the water pipes are shown in Figure 23.

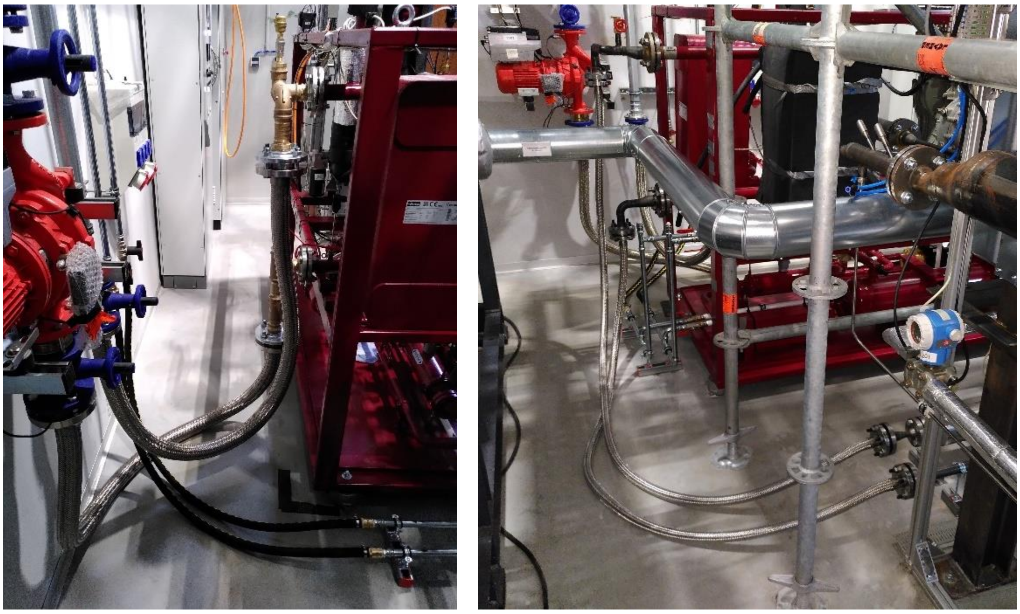

Figure 23: ORC – Hose connections between condenser, expander cooling, subcooler and CWDN (left) and between preheater and SH-TESS water circuit (right)

[3] The chopper cabinet contains braking modules (choppers) which dissipate the produced electricity in a controlled manner (in case of power failure) with the resistive heaters located below the cabinet.

Task 3.3 – Filling of water circuits and leak test:

As described in section 3.2 and 4.2, the water circuits were filled with softened water according to VDI2035. After pressurization to 5 bar, a leak test was successfully performed and all hoses were insulated in order to minimize heat loss to the environment.

Task 4.1 – Check of nitrogen pressure:

Before shipping, the refrigerant circuit was filled and pressurized with nitrogen. In order to determine whether leaks occurred during transport, the nitrogen pressure was checked after the prototype was assembled. During the pressure check, if the pressure tends to zero, the leakage must be found and repaired or sealed accordingly. A nitrogen pressure of 5.7 bar was measured in the refrigeration circuit using an appropriate pressure gauge, so that a leakage could be ruled out.

Task 4.2 – Connection between ORC and LH-TES:

As described in section 3.4, the ORC was directly connected to LH-TES unit via steel pipes and flanges. The pipe connections between ORC prototype and LH-TES unit are shown in Figure 24.

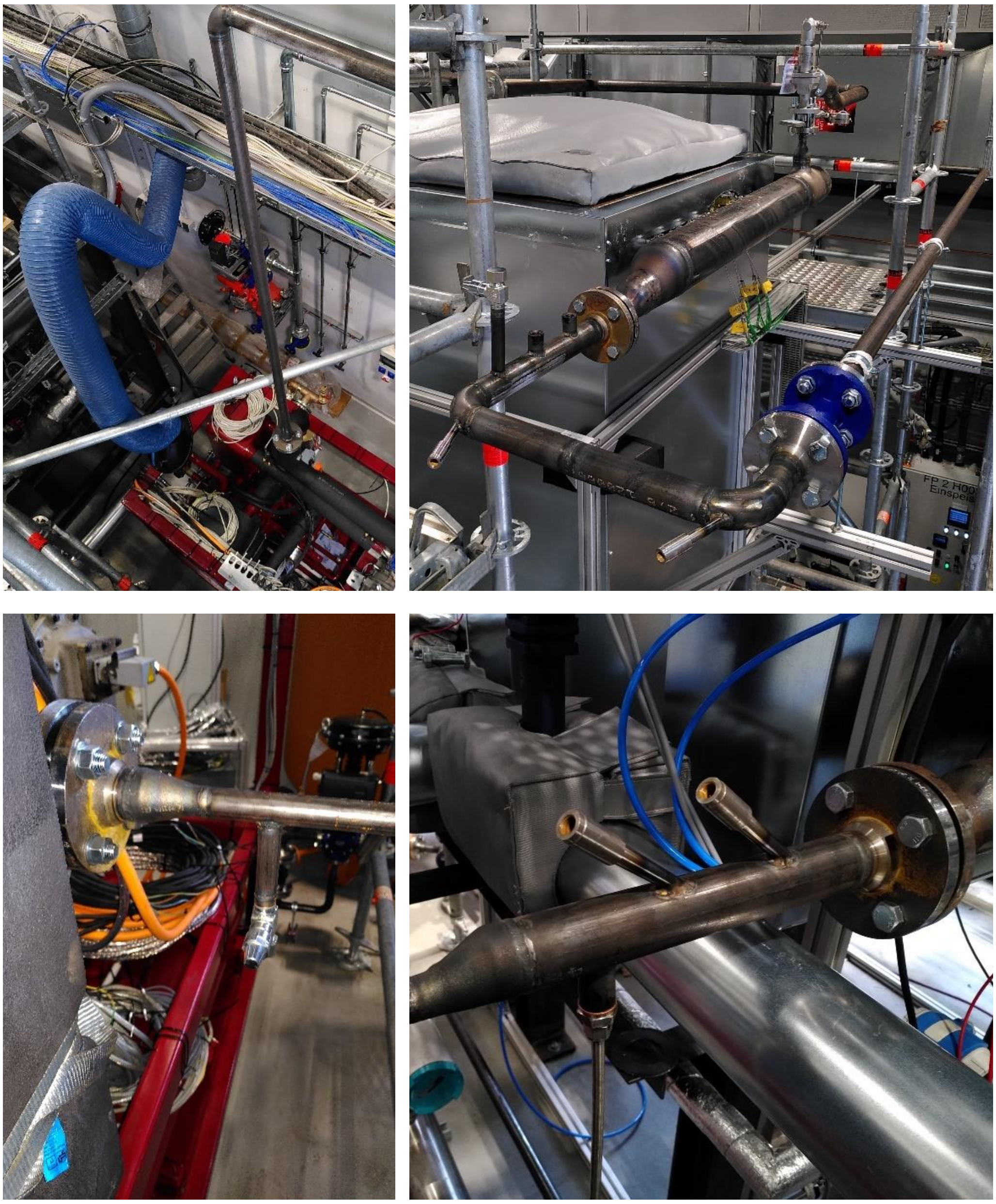

Figure 24: ORC – Pipe connections between ORC prototype and LH-TES unit. ORC expander inlet (top left), LH-TES outlet (top right), ORC preheater outlet (bottom left) and LH-TES inlet (bottom right)

Task 4.3 – Filling of expander with the lubricant:

Before the lubricant could be filled, first the nitrogen had to be released from the refrigerant circuit. Then, approx. 7 kg of the lubricant was filled into the filter cartridge and via the designated charging port into the crank case of the expander. Thereafter, the connections were closed and residues were removed.

Task 4.4 – Charge of refrigerant and leak test:

The refrigerant circuit must be charged in two steps as the ORC commissioning (described in Task 7.1 and 7.2 below) includes a first startup without the LH-TES unit, followed by further test runs together with the entire HT-TESS. For this purpose, the LH-TES unit was first decoupled from the ORC via internal shut-off valves. Then, the storage side with the discharging register, the headers and the piping were pressure tested. After the nitrogen was released, both sides of the refrigerant circuit (ORC and LH-TES unit) were evacuated. Once the necessary vacuum was reached, the ORC side was charged with 69 kg of the refrigerant R1336mzz(E) and the initial startup was conducted. For the second test run, the LH-TES side was charged with 61 kg of the same refrigerant. A leak test concluded this task.

Task 5.1 – Wiring between ORC and control cabinet:

The ORC also includes a control cabinet and a chopper cabinet, which were assembled next to the prototype (see Task 2.2). Within Task 5.1, the electrical components in the prototype, such as sensors, pumps, actuators, etc., were connected to the respective cabinet.

Task 5.2 – Power up the control cabinet:

The control cabinet of the ORC was connected to the feed-in point in the laboratory and the power supply was tested. Figure 25 shows the feed-in point, control and chopper cabinet of the ORC prototype.

Figure 25: ORC – Feed-in point (left), control cabinet (left) and chopper cabinet (right)

Task 6.1 to 6.4 – Operational check:

These tasks include the commissioning of the control cabinet and a functional test of the ORC components. Therefore, the PLC and the PC are switched on and it was checked if the values from the sensors are read and displayed correctly, if components like expander, pumps and valves are working properly and if a remote access via the internet connection is possible. After the check, the control system was prepared for the initial startup of the ORC.

Task 7.1 – ORC test run with preheater only:

The commissioning of the ORC was carried out in two steps in order to minimize the risks of damage and to define the optimal amount of refrigerant for the operation together with a HT-TESS. For the first test run, the LH-TES was decoupled from the ORC via internal shut-off valves. This configuration was chosen because the amount of refrigerant was already known from individual prototype tests at the laboratory of

UGent and transient effects during the initial startup were minimized. The preheater is used here for both preheating and evaporating the refrigerant.

Before the ORC was started, the SH-TESS was heated by the electrical immersion heater; hot water at 130 °C was then supplied to the preheater. In addition, the pumps in the condenser and subcooler water circuits as well as the oil heaters in the expander crankcase were activated. Once the setpoint temperatures were reached, the refrigerant pump was started and the speed was slowly increased. During this phase, the refrigerant flow was bypassed directly to the condenser until the required vapor conditions were achieved. Then, the expander was started by gradually closing the bypass. The expander speed was increased until a steady operating point was reached. In order to maintain constant vapor conditions, the water mass flow in the preheater was constantly adjusted between 0.1 and 0.25 kg/s via the lab control system. After approx. 60 min of steady operation, the ORC was shut down again in reverse order and switched off.

Task 7.2 – ORC test run with full HT-TESS:

For the next test run, the valves to the LH-TES unit were opened and refrigerant was additionally charged, resulting in a total amount of 130 kg. In addition, the LH-TES unit was heated to a mean PCM temperature of approx. 130 °C using the steam generator.

First test run

Following the same startup procedure as previously described in Task 7.1, first hot water at 130 °C was fed to the preheater, the oil in the expander crankcase was heated and the supply of cooling water was activated. After reaching the setpoint temperatures, the refrigerant was pumped through the preheater and the LH-TES unit until the required vapor conditions were achieved. By closing the bypass gradually, the expander was stared for the first time together with the entire HT-TESS. During the first test run, a steady operating point could be achieved for about 67 minutes at an expander speed of approx. 800 rpm. A power output of about 6 kWel was achieved. However, these values are not representative, as this was an initial startup and therefore only reflecting operating conditions during this test run. In the first test run, some problems were observed during the startup of the expander, due to the high refrigerant charge in the system. Refrigerant was extracted, resulting in a new total amount of 110 kg.

Second test run

A second test run was conducted under the same conditions as described before with the reduced amount of refrigerant. Again, a steady operating point for about 56 minutes could be achieved at an expander speed of approx. 800 rpm, resulting in a power output of about 6 kWel.

The main parameters of the steady operating points achieved during ORC commissioning are shown in Table 8.

Table 8: ORC commissioning: main parameters of the steady operating point

Description	Unit	Value
First test run:		
Refrigerant charge	kg	130
Expander speed	rpm	800
Expander inlet temperature	°C	118
Expander inlet pressure	bar	16.5
Refrigerant mass flow during steady state operation	kg/s	0.411
Time in which a steady state was achieved	min	67
Second test run:		
Refrigerant charge	kg	110
Expander speed	rpm	800
Expander inlet temperature	°C	117
Expander inlet pressure	bar	16.9
Refrigerant mass flow during steady state operation	kg/s	0.440
Time in which a steady state was achieved	min	56

4.4. Commissioning of the HTHP

The HTHP prototype was prepared for commissioning according to a setup task list provided by Tecnalia. The tasks required for commissioning are presented in Table 9 and described below.

Table 9: Setup task list for the HTHP prototype

Category	Task No.	Task
1. Arrival	1.1	Unboxing and transport to the final position in the lab
2. Preliminary check	2.1	Visual check of internal piping and components
	2.2	Check of control/power cabinet
3. Water circuits	3.1	Connection of water pipes
	3.2	Filling of water circuits and leak test
4. Refrigerant circuit	4.1	Check of nitrogen pressure
	4.2	Connection between HTHP and LH-TES
	4.3	Filling of lubricant to the compressor
	4.4	Charge of refrigerant and leak test
5. Wiring	5.1	Power up the control cabinet
6. Operational	6.1	Check operation of water pumps
	6.2	Check operation of heaters
	6.3	Check operation of valves
7. Startup	7.1	Run HTHP with the full HT-TESS

Task 1.1 – Unboxing and transport to the final position in the lab:

After delivery, the HTHP prototype was transported to the designated location in the laboratory and the protection wrapping that protected the HTHP during transportation was removed. The prototype was aligned to the CHEST lab system.

Task 2.1 – Visual check of internal piping and components:

The visual check serves to identify damages that may have occurred during transport. Therefore, the interior of the prototype was inspected for loose components, missing insulation, bent or broken sensors, cut cables, etc. The visual inspection was documented with a video and photos (see Figure 26). During the check, a few minor damages were detected. Some of the glue joints of the insulation were broken and some parts were damaged (see Figure 26, top left), some caps of the valves are missing, including the cap of the Schrader valve (see Figure 26, middle left and right), and some of the connections are bent for some of the subcooler connections and the refrigerant outlet (see Figure 26, bottom left and right).

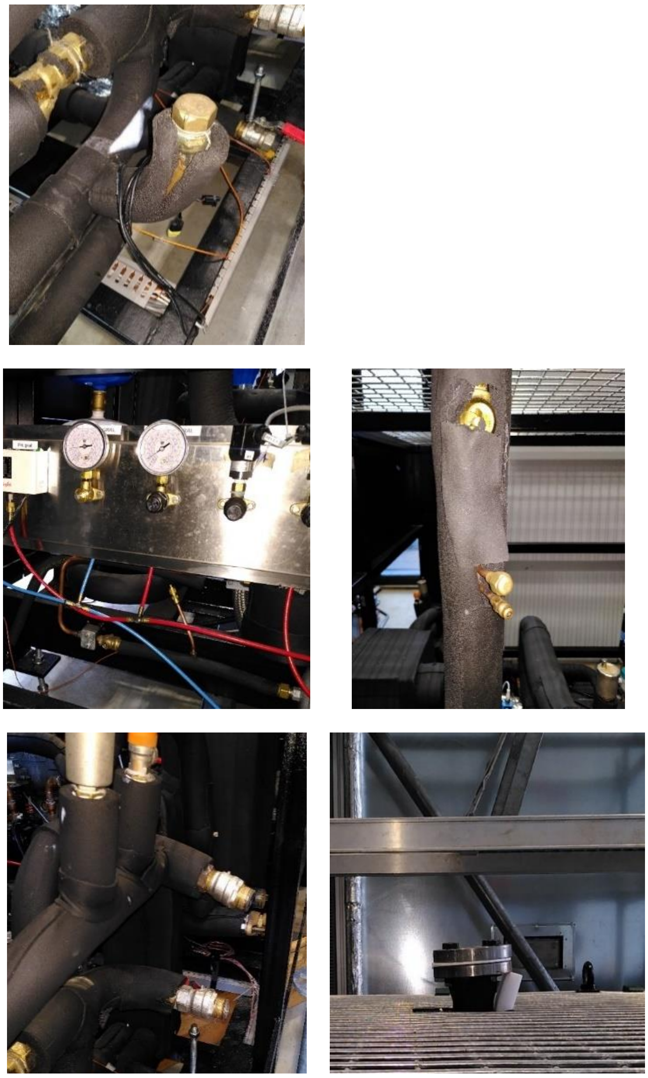

Figure 26: HTHP – Pipeline and components. Damaged insulation and broken glue joints (top left). Caps missing at the left manometer (middle left). Caps missing at the Schrader valve (middel right). Subcooler connections are bent (bottom left). The refrigerant outlet is bent (bottom right)

Task 2.2 – Check of control/power cabinet:

This task includes the assembly of the control and power cabinet as well as a visual check for potential transport damages. The control cabinet was inspected for i.e. loose connections, detached components, damaged cables. The visual inspection was documented with photos. During the check, some loose components were found in the control cabinet, but no major damages were detected (see Figure 27).

Figure 27: HTHP – loose parts in the control/power cabinet.

Task 3.1 – Connection of water pipes:

As described in Section 3.5, the HTHP and the heat source and the HTHP and SH-TESS are connected using hoses. These are shown in Figure 28.

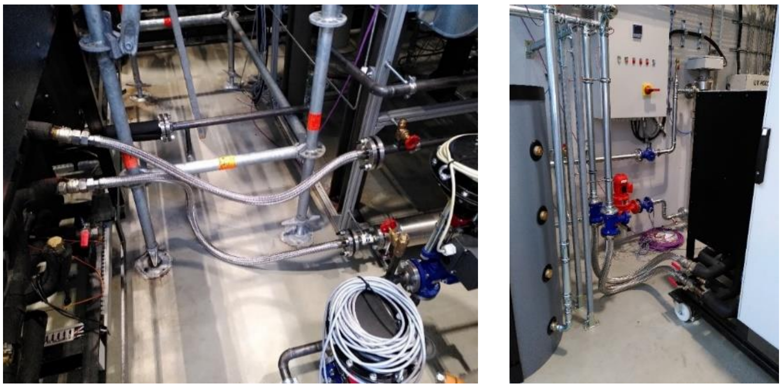

Figure 28: HTHP connections. Hose connection between HTHP and SH-TESS loop (left). Hose connection between HTHP and heat source (right)

Task 3.2 – Filling of water circuits and leak test:

The water circuits were filled with softened water according to VDI2035. After pressurization to 2 bar, a leak test was successfully performed and all hoses were insulated in order to minimize heat loss to the environment.

Task 4.1 – Check of nitrogen pressure:

Before shipping, the refrigerant circuit was filled and pressurized with nitrogen. In order to determine whether leaks occurred during transport, the nitrogen pressure was checked after the prototype was assembled. During the pressure check, if the pressure tends to zero, the leakage must be found and repaired or sealed accordingly. A nitrogen pressure of 2.5 bar was measured in the refrigeration circuit using an appropriate pressure gauge, so that a leakage could be ruled out (s. Figure 29).

Figure 29: Manometers indicate a N_2 pressure of approx. 2.5 bar after shipping

Task 4.2 – Connection between HTHP and LH-TES:

In order to connect the HTHP to the LH-TES an extension was mounted at the HTHP, as shown in the Figure 30. left. After this the HTHP discharge line and return line were soldered to the HTHP (s. middle and right).

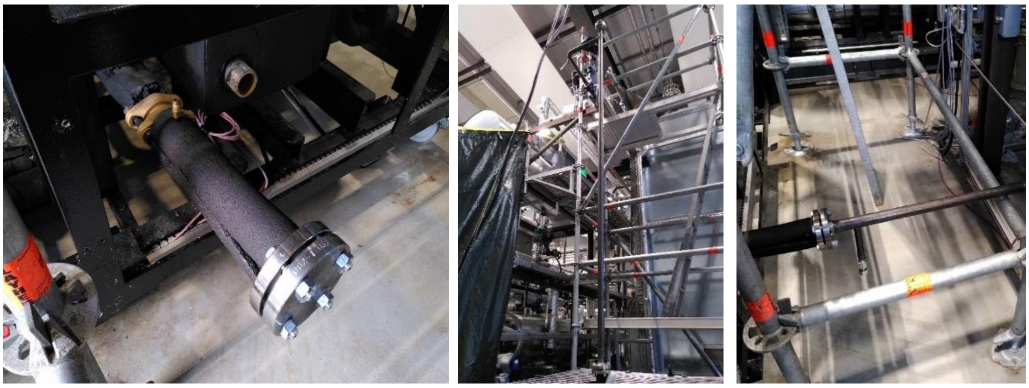

Figure 30: Connection HTHP to the LH-TES. Extension of HTHP return connection (left). HTHP discharge line (middle). HTHP return line (right).

Task 4.3 – Filling of lubricant to the compressor:

Before the lubricant could be filled, first the nitrogen had to be released from the refrigerant circuit. Then, the lubricant was filled into the filter cartridge and via the designated charging port into the crank case of the compressor. Thereafter, the connections were closed and residues were removed.

Task 4.4 – Charge of refrigerant and leak test:

The refrigerant circuit between HTHP and the LH-TES was inspected, for this a leakage test was carried out. The circuit was then vacuumed and filled refrigerant R1233zd(E). Unlike the ORC, the filling of refrigerant to this circuit was done in one step only. The flow diagram is included in the Annex at the end of this deliverable.

Task 5.1 – Power up the control cabinet:

The control cabinet of the HTHP was connected to the feed-in point in the laboratory and the power supply was tested.

Task 6.1 to 6.3 – Operational check:

These tasks include the commissioning of the control cabinet and a functional test of the HTHP components. Therefore, the PLC and the PC are switched on and it was checked if the values from the sensors are read and displayed correctly, if components like compressor, pumps and valves are working properly and if a remote access via the internet connection is possible. After the check, the control system was prepared for the initial startup of the HTHP.

Task 7.1 Run HTHP with the full HT-TESS:

In order to ensure optimal startup conditions for the HTHP prototype, the HT-TESS and heat source were preconditioned. Therefore, the LH-TES unit was heated by the steam generator to approx. 120 °C, which is slightly below the temperature were the PCM starts to melt. The cold tank of the SH-TESS was heated by the electrical immersion heater to a water temperature of 70 °C and the primary circuit of the heat source to a water temperature of 95 °C. In addition, the electrical trace heaters in the crankcase of the compressor and on specific pipe sections inside the HTHP prototype were activated. Once the setpoint temperatures were reached, the compressor was started. Then the compressor speed was gradually increased until a discharging pressure of approx. 22 bar was achieved. After the HT-TESS was charged for more than 60 minutes, a steady operation could be observed over a period of about 20 minutes at a compressor speed of 1300 rpm. During the test run, the water mass flows were maintained between 0.01 and 0.1 kg/s in the subcooler and around 3.5 kg/s in the evaporator, while the water temperature from the heat source was maintained at a constant value of 90°C.

The main parameters of the steady operating point achieved during HTHP commissioning are shown in Table 10.

Table 10: HTHP commissioning: main parameters of the steady operating point

Description	Unit	Value
Compressor speed	rpm	1300
Compressor discharging temperature	°C	144
Compressor discharging pressure	bar	22.6
Refrigerant mass flow during steady state operation	kg/s	0.23
Time in which a steady state was achieved	min	20

5. Conclusions

The installation and commissioning of the components and whole compressed thermal energy storage (CHEST) prototype has been completed. The high temperature thermal energy storage system (HT-TESS), the organic Rankine cycle (ORC) and the high temperature heat pump (HTHP) were tested individually (as reported in the deliverables D3.7, D3.8 and D3.6) and delivered to the laboratory (the HT-TESS was tested at this laboratory), installed and commissioned there. For this process, the components were individually commissioned in the lab environment and functionality tests conducted.

The installation of the HT-TESS was done in two steps, as the LH-TES unit was tested and characterized in a first step before integration with the overall CHEST laboratory prototype system. This commissioning was described in D3.7 and involved the multi-step filling of the storage unit with PCM, mounting of measurement equipment and installation of trace heating around the LH-TES.

The SH-TES system actively interacts with the subcooler of the HTHP and the preheater of the ORC during operation. Thus, the commissioning procedure includes, besides the filling with the storage medium, also a functional check of the control loops implemented in the laboratory control system.

The installation and commissioning of the ORC included the transport-check and initial startup checks of the ORC, the physical attachment to the piping and instrumentation of the lab and the HT-TESS and an initial operation run. In the first operation run, there were issues with the operation of the expander. After an adjustment to the refrigerant amount in the system, a second operating run was conducted. In this second run, there were no operation issues with the expander or other components, and the system operated well. Therefore, it can be concluded that a good fill level of the refrigerant has been attained.

The installation of the HTHP was conducted similarly to that of the ORC. The initial operating run of the HTHP was successful and it was possible to prove that it is possible to charge the HT-TESS with the HTHP.

With the successful commissioning of all of the subcomponents of the CHEST laboratory prototype, a proof of concept of the CHEST system has been achieved and milestone MS7 reached.

Annex

A.1. Piping and instrumentation diagram of the laboratory CHEST system (version 8)