CHESTER
Compressed Heat Energy Storage for Energy from Renewable sources

Laboratory test site completely prepared

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Glossary, abbreviations and acronyms

CHEST	Compressed Heat Energy Storage
HT	High temperature
LH	Latent heat
SH	Sensible heat
TES	Thermal energy storage
TESS	Thermal energy storage system
PCM	Phase change material
HP	Heat pump
ORC	Organic Rankine Cycle
P&ID	Piping and Instrumentation Diagram
PLC	Programmable logic controller
SCADA	Supervisory control and data acquisition
GA	Grant Agreement

1. Introduction

1.1. Executive Summary

The main objective of WP5 is to successfully build and operate a laboratory first-of-its-kind CHEST system, to experimentally analyze the feasibility of various operation modes and the corresponding efficiencies. T5.1 comprises the preparation of the laboratory for the installation of the overall CHEST system. This includes the preparation of the laboratory space, the electricity supply for the individual prototypes and the connections to the cooling water network. Safety devices and an exhaust air system were also prepared based on the safety data sheets of the substances applied and the operating parameters envisaged for the experiments. Another subtask involved the development of the data acquisition and control system architecture and the design of the corresponding components. Moreover, the system layout was planned and the required laboratory infrastructure for the operation of the test rig was prepared.

1.2. Purpose and Scope

The objective of this deliverable is to summarize the work carried out (within T5.1) to prepare the DLR premises for the installation of the overall laboratory CHEST system and the experimental phase of the project.

1.3. Methodology

The laboratory preparations were carried out according to the individual subtasks defined for T5.1 in the Grant Agreement (GA). The preparation of safety equipment in the laboratory is based on material data of the substances applied and the operating parameters envisaged for the experimental analysis of the CHEST system. The development of the data acquisition and control system was conducted in close collaboration between the partners of WP3 and WP5, as there are several interfaces between the individual prototypes and the laboratory control system. In order to determine the optimal system layout and to plan the piping between the components, a three-dimensional drawing was developed. The design of the required laboratory infrastructure was based on the technical specifications of the individual prototypes provided by the partners of WP3.

1.4. Structure of the document

This document is divided in two main sections.

Section 2 contains a detailed description of the work carried out on the corresponding subtasks of WP5.1 and technical specifications concerning the laboratory and its infrastructure.

In section 3, the main achievements of T5.1 are summarized.

1.5. Relations with other deliverables

This work package is closely related to WP3, specifically to T3.1 (D3.2), T3.2 (D3.3) and T3.3 (D3.4), as the arrangement of the laboratory CHEST system mainly depends on the final design of the individual prototypes. Also, additional safety devices and the laboratory infrastructure are prepared according to the substances that are tested in and integrated into the individual prototypes and to the operational parameters defined in these work packages.

2. Preparation of the laboratory

According to the GA, WP5.1 is comprised of six subtasks, which are listed in Table 1. This section contains a detailed description of the work carried out on the corresponding subtasks and technical specifications concerning the laboratory and its infrastructure.

Table 1: Overview of WP5.1

Task	Title
5.1.1	Preparation of laboratory space, electrical connections, cooling water network
5.1.2	Preparation of safety devices and exhaust air system
5.1.3	Preparation of data acquisition and control system
5.1.4	Planning of the system layout and the pipe connections between the components
5.1.5	Design and installation of the temperature-controlled heat source and heat sink
5.1.6	Preliminary installation of the high temperature thermal energy storage

2.1. Laboratory space

Task 5.1.1 includes the preparation of the laboratory space at DLR facilities in Stuttgart. All experimental work within tasks 5.2 to 5.4 will be performed in the laboratory H003. Figure 1 shows the corresponding floor plan with an area (red dotted lines) of approximately 50 m², which is available for the installation of the laboratory CHEST system. The white areas are currently required for the operation of test rigs from other projects and laboratory infrastructure.

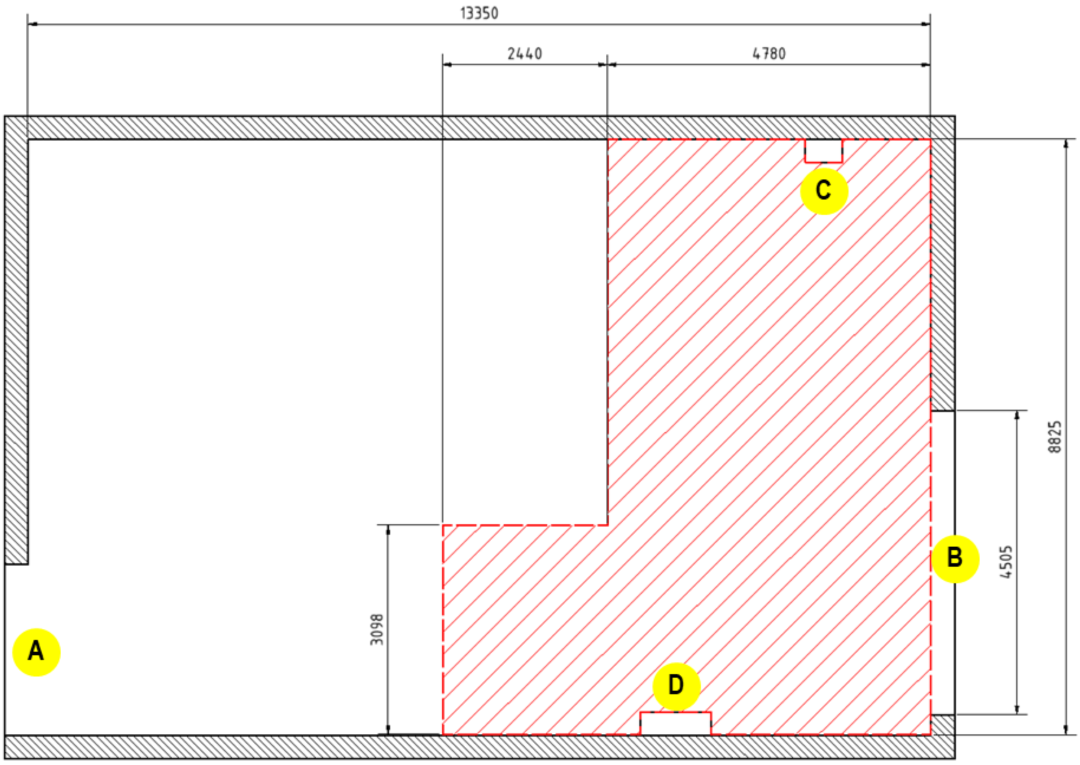

Figure 1: Available area (red dotted lines) for the installation of the CHEST system at DLR laboratory H003

The laboratory has two doors, marked by the letters A and B in Figure 1. A is the main access from the building side and cannot be used for heavy loads. B has large dimensions and can be approached directly by the transporter for delivery of heavy components and materials. In the laboratory, loads up to 2000 kg can be handled with the stationary overhead crane. The relevant technical specifications of the laboratory H003 are summarized in Table 2.

Table 2: Technical specifications of laboratory H003

Description	Unit	Value
Clear length (H003)	mm	13350
Clear width (H003)	mm	8825
Effective height (H003)	mm	5500
Total area available for the laboratory CHEST system	m^2	≈50
Clear width (door A)	mm	2150
Clear height (door A)	mm	2450
Clear width (door B)	mm	4505
Clear height (door B)	mm	4100
Maximum area load (Floor)	kg/m^2	8000
Maximum load capacity (overhead crane)	kg	2000

As cable trays are installed on the walls of the laboratory, the height of components to be placed in this area is limited to 2950 mm. According to the planned arrangement of the laboratory CHEST system described in paragraph 2.5, this mainly affects the design of the SH-TES tanks and the buffer tank of the heat source.

In order to provide the required space for the installation of the individual prototypes, the main work carried out in this subtask comprised the disassembly and removal of existing test rigs and its infrastructure from the laboratory H003.

2.2. Electrical connections and cooling water network

Another objective of task 5.1.1 is to prepare the electrical connections and the cooling water network for the laboratory CHEST system. The former comprises both the supply of electrical energy to all components of the test rig and the feed-in of electrical energy into the grid. The corresponding electricity connections were prepared in the laboratory H003 according to the technical specifications of the individual prototypes. Figure 1 shows the positions of the main electricity supply and the feed-in point for the organic Rankine cycle (ORC), marked by the letters C and D, respectively. The relevant technical specifications required for operating the high temperature heat pump (HT-HP) and the ORC are summarized in Table 3.

Table 3: Technical specifications of the electrical connections for the HT-HP and the ORC

Main electricity supply	Unit	Value
Voltage	V	400
Main protection	A	63
Line frequency	Hz	50
Feed in point		
Maximum capacity	kW_{el}	15,5
Amperage	A	35
Line frequency	Hz	50

DLR has a central cooling water network for the laboratories. The pipe network is designed as a semi-open ring system and can provide cooling water with a temperature of 11 °C. The return temperature in the primary circuit is limited to 17 °C, since polymers are used as the pipe material. The work carried out for the preparation of the cooling water network mainly included the evaluation of the available cooling capacity based on technical documents as well as the preparation of the cooling water connections in laboratory H003, which are shown in Figure 2.

Figure 2: Connection to the cooling water network

Table 4 shows the technical specifications of the cooling water network, which were used as a basis for the design of the temperature controlled heat sink, described in paragraph 2.6.

Table 4: Technical specifications of the cooling water network

Description	Unit	Value
Cooling water inlet temperature	°C	11
Maximum return temperature	°C	17
Available cooling capacity	kW	150
Pipe dimensions	DN	100
Nominal pressure	PN	10

2.3. Safety devices and exhaust air system

Task 5.1.2 comprises the preparation of safety devices and an exhaust air system at DLR premises. Laboratory H003 provides modern basic safety equipment, in accordance to the applicable regulations. This includes a fire extinguisher (FE), first aid equipment (FA) and an eye wash (EW). A defibrillator is available in the building. In addition to the modern basic safety equipment, an emergency shower (ES) was installed in the laboratory. To stop the operation of machines or components of the test rig in case of emergency, the laboratory is equipped with several kill switches (KS). Figure 3 shows the positions of the laboratory safety equipment marked in green and the exits A and B, to be used in emergencies, marked in yellow.

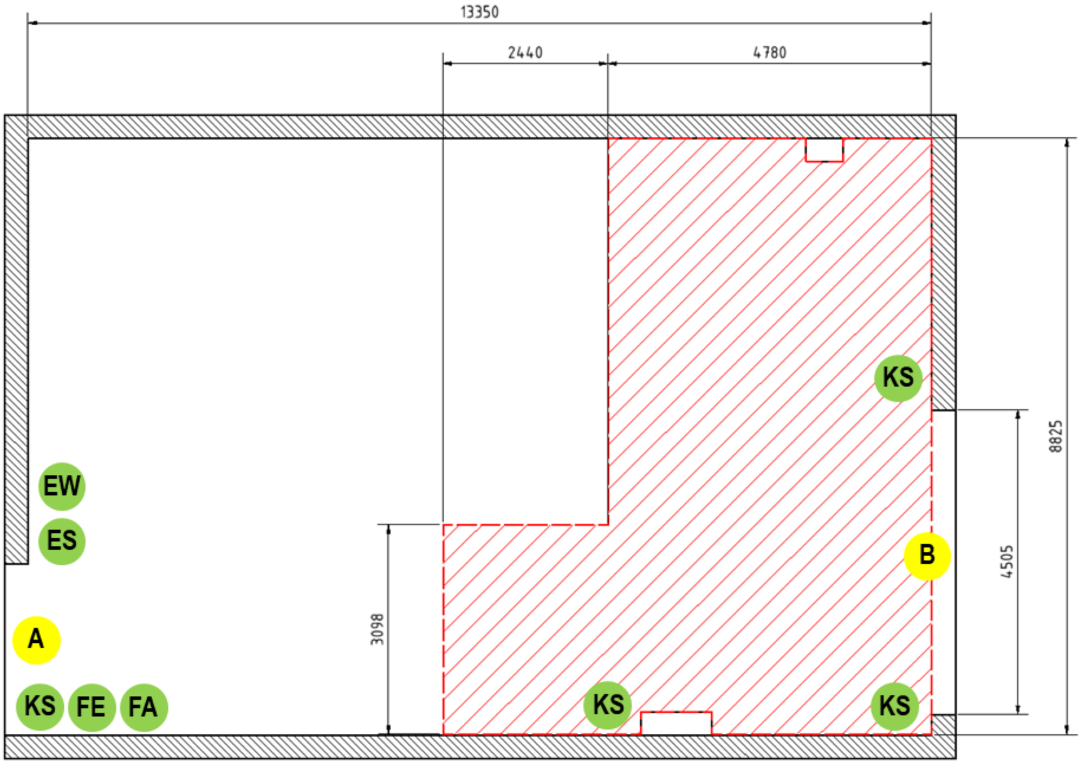

Figure 3: Available safety devises (green) and emergency exits (yellow) of the laboratory H003

Based on the material safety data sheets of the refrigerants used in the laboratory CHEST system, a risk assessment was carried out and operating instructions were created in accordance with § 4 of the German Hazardous Substances Ordinance (GefStoffV). As both substances are non-flammable, only measures to prevent direct contact and inhalation must be taken. Therefore, all persons working in the laboratory must wear appropriate protective clothing and all persons working on the rig must follow the operating instructions. In case of skin contact, an emergency shower is available in the laboratory, as shown in Figure 4.

Figure 4: Emergency shower in laboratory H003

In order to avoid the inhalation of dust, fume, gas, mist or vapors and to maintain a high air quality in the laboratory while operating the test rig, an exhaust air system was installed. The system has a capacity of 4500 m³/h and is currently equipped with a flexible hose connection, which allows for the extraction of exhaust air at a specific spot. Further connections can be added if required. Figure 5 shows the exhaust air system of laboratory H003.

Figure 5: Exhaust air system of laboratory H003

In addition to the exhaust air system, a blow-out line for the safety valves was installed in the laboratory. Appropriate connections for the installation of the individual prototypes were already prepared, as shown in Figure 6.

Figure 6: Section of the blow-out line with a flange prepared for the prototype's safety valves lines

2.4. Data acquisition and control system

The objective of task 5.1.3 is the planning and installation of the data acquisition and control system for the laboratory CHEST system. This also includes the definition and preparation of the interfaces between the individual prototype controllers and the superordinate control system of the laboratory as well as the development of suitable control strategies for different operating modes. Therefore, this task requires a close collaboration between the partners of WP3 and WP5.

2.4.1. Control system architecture

Figure 7 gives an overview of the control system architecture planned for the laboratory CHEST system. The main components of the system are the HT-HP, the high temperature thermal energy storage system (HT-TESS) and the ORC.

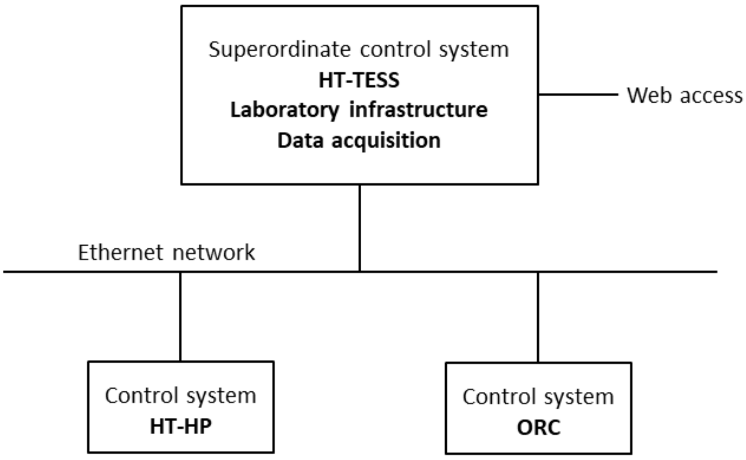

Figure 7: Overview of the control system architecture

The HT-HP and the ORC are controlled by individual control systems developed by the partners responsible for the manufacturing of the prototypes in WP3. This allows for the independent development of control algorithms and safety-relevant functions according to the operational requirements of the specific prototype. The individual controllers are connected via an Ethernet network to a supervisory control and data acquisition (SCADA) system. The SCADA is used for the control of the HT-TESS and the laboratory infrastructure as well as for a real-time visualization of the system operation, to change controller set points and for data acquisition. In order to provide online access for the partners, a public LAN network will be established.

A schematic of the HT-HP control system is depicted in Figure 8. The main components of the system are the Beckhoff CX8180 programmable logic controller (PLC), a panel computer unit and a Siemens inverter. All process parameters of the HT-HP, including analog and digital signals for corresponding field devices, are controlled by the Beckhoff PLC. The panel computer unit comprises a computer system with a database and a monitor to visualize specific process parameters during operation. The inverter is connected to the PLC via PROFINET (or process field net) and controls the compressor of the heat pump. PROFINET is an industrial standard for data communication over industrial Ethernet networks. Further components such as the expansion valve, internal heaters or sensors are connected to the PLC via Modbus, which is a serial communications protocol for the connection of industrial electronic devices. An Ethernet network is used to connect the HT-HP controller to the superordinate laboratory SCADA system.

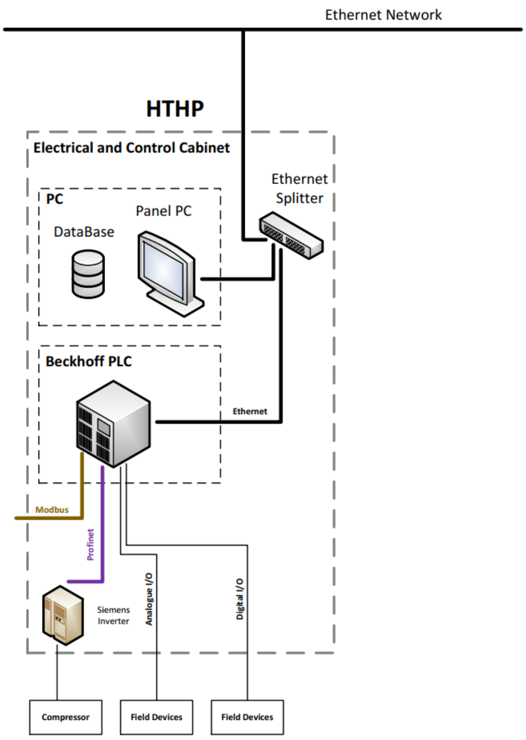

Figure 8: Main components of the HT-HP control system

The main components of the ORC control system are shown in Figure 9. These are a Siemens S7 PLC, a panel PC unit, an embedded controller and drivers for expander and pump motor.

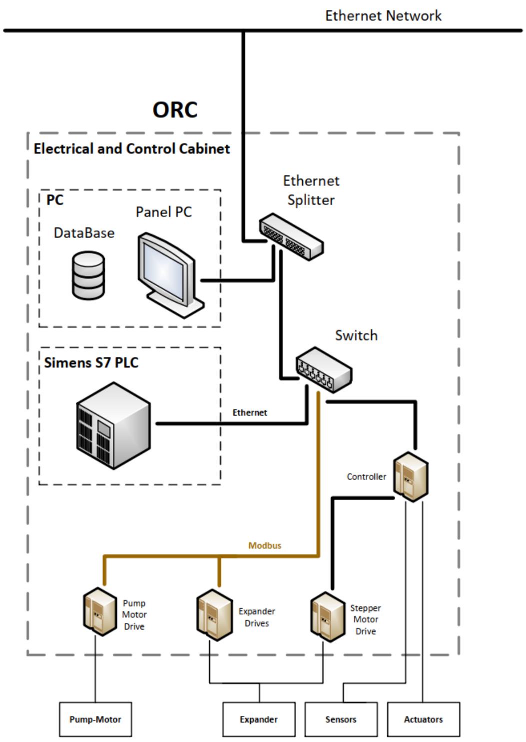

Figure 9: Main components of the ORC control system

All processes parameters of the ORC are controlled by the Siemens PLC. The panel PC unit also comprises a computer system with a data base and a monitor to visualize specific process parameters during operation. The embedded controller is connected to the PLC via an Ethernet switch and controls the actuators such as valves or contactors. Also, the input signals from the sensors are processed by this component. For the control of the expander, a stepper motor drive and expander drives are used. The stepper motor drive is connected to the embedded controller and the expander drives to the switch. The feed pump of the ORC is controlled by a pump motor drive, which is also connected to the switch. Modbus is used for the communication between switch, expander drives and pump motor drive. The ORC control system is connected to the superordinate laboratory SCADA system via an Ethernet network.

Figure 10 shows the architecture of the laboratory SCADA system. The main components are a Siemens S7 PLC and a panel PC unit. The PLC controls the HT-TESS and laboratory infrastructure via PROFIBUS DP (Decentralized Peripherals). In order to control various field devices, the PLC has also analog and digital connections. The panel PC unit with the database is used for the adjustment of set points and for data acquisition. In addition, the monitor allows a real-time visualization of the system operation. The Ethernet router is required to connect the individual control systems of the prototypes to the superordinate SCADA system.

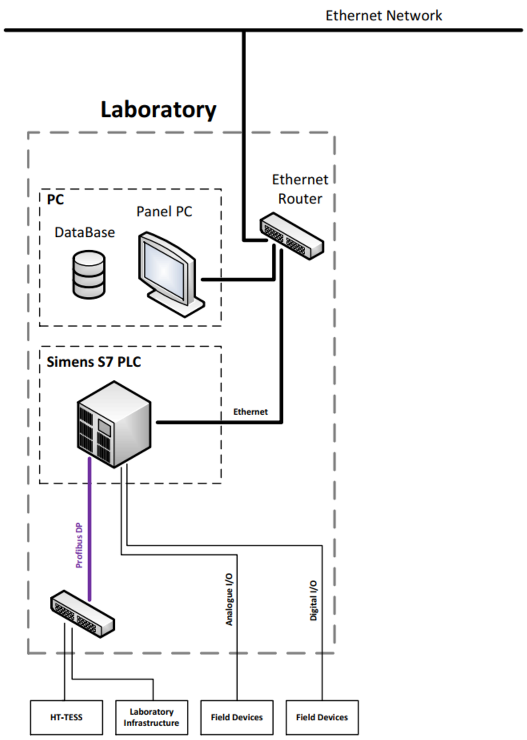

Figure 10: Main hardware components of the SCADA

2.4.2. Measuring and control variables

All control variables of the overall laboratory CHEST system are summarized in a common Excel document. The document is collaboratively created by the partners of WP3 and WP5. Thus, a uniform nomenclature for the data acquisition is achieved and all information is available in one place. The basic structure of the document is shown in Figure 11. Each component has a specific spreadsheet with a corresponding excerpt from the piping and instrumentation diagram (P&ID). The current version of the P&ID can be found in annex A.1. In the first column (starting from the left side) the measuring points are listed according to the P&ID tag numbers.

The second column contains the variable label used in the data base which has the following nomenclature.

System_Component_Sub-component(s)_Fluid stream_Connection_Type of value_Modifier

The first part indicates the system, e.g. HT-HP, ORC or LH-TES, followed by the corresponding component, e.g. evaporator, compressor or expander. Sub-components such as heater, pump or energy meter can be used to specify the component, if required. Fluid stream indicates the appropriate working fluid, e.g. cooling water, heating water or refrigerant. The connection type is described with inlet, outlet or blow-out line, followed by the type of value, e.g. temperature (T), pressure (P) or mass flow (m). Modifiers such as set point, max alarm or hysteresis can be added if necessary.

Measuring point designation (P&ID tag number)	Variale label (used in data base)	Type of variable	Read/write	Measured quantity	Min value	Max value	Unit
PDI201	LH-TES_LH-TES_HP_refr_in_out_PD	real	read	P difference			mbar
PDI205	LH-TES_LH-TES_ORC_refr_in_out_PD	real	read	P difference			mbar
P202	LH-TES_LH-TES_HP_refr_in_P	real	read	P	0	40	bar

Accuracy	Fluid	Operating conditions	Connection type	Output signal	Measuring principle	Type of the measuring device	Notes
	R1233zd(E)	22bar 150°C		4-20mA		E+H Deltabar	
	DR-12	24bar 150°C		4-20mA		E+H Deltabar	
0,05%	R1233zd(E)	22bar 150°C		4-20mA		E+H Cerabar PMC71	

Figure 11: Excerpt from the common document

The variable type is specified in the next column. These can be data types such as integer, floating point (real) or Boolean. This is followed by the information whether the variable has read, write or read and write access. The next columns contain the measured quantity, minimum and maximum value, the unit of the measured quantity and the accuracy of measuring device. Then the table includes information on the working fluid, operating conditions and connection type. This is followed by the output signal, the measuring principle and the type of measuring device. The last column can be used for notations.

The HT-HP and the ORC can be remotely controlled by the superordinate laboratory SCADA system by means of specific read and write variables. Table 5 shows an example of variables and the corresponding actions defined for the control of the HT-HP.

Table 5: Variables for remote control of the HT-HP

Variable Label	Description	Action
HTHP_HMI_Standby	HMI button: Standby	Sets the “standby” state
HTHP_HMI_Start	HMI button: Start	Sets the “start” state
HTHP_HMI_Stop	HMI button: Stop	Sets the “stop” state
HTHP_Ev_Water_DT_Setpoint	Evaporator’s water side temperature difference set point	Set the DT in Kelvin to be achieved in the evaporator’s water side flow. It controls the evaporator’s water pump speed.
HTHP_Sc_DT_Setpoint	Subcooler’s temperature difference setpoint	Setpoint of the temperature difference in between the subcooler’s refrigerant inlet and water outlet. This controls the subcooler’s water pump speed.

2.4.3. Chester prototype control strategies

In order to operate the laboratory CHEST system, basic control strategies were developed and discussed among the partners involved. In addition to the strategies required for charging and discharging, system start-up and conditioning between the experiments were also considered. The resulting control strategies planned for the system operation are described in the following section.

Charging process

In this process, the HT-HP is used to charge the HT-TESS under various operating conditions. Figure 12 shows an excerpt from the P&ID containing HT-HP circuit, LH-TES unit, SH-TESS, temperature-controlled heat source and cooling water distribution. The components in the refrigerant circuit (green) such as compressor C140 or expansion valve V102 as well as the pumps P150 and P160 in the water circuits are controlled by the HT-HP control system. The laboratory Siemens PLC controls the components of the heat source and the cooling water distribution. Corresponding setpoints are entered or adjusted in the SCADA.

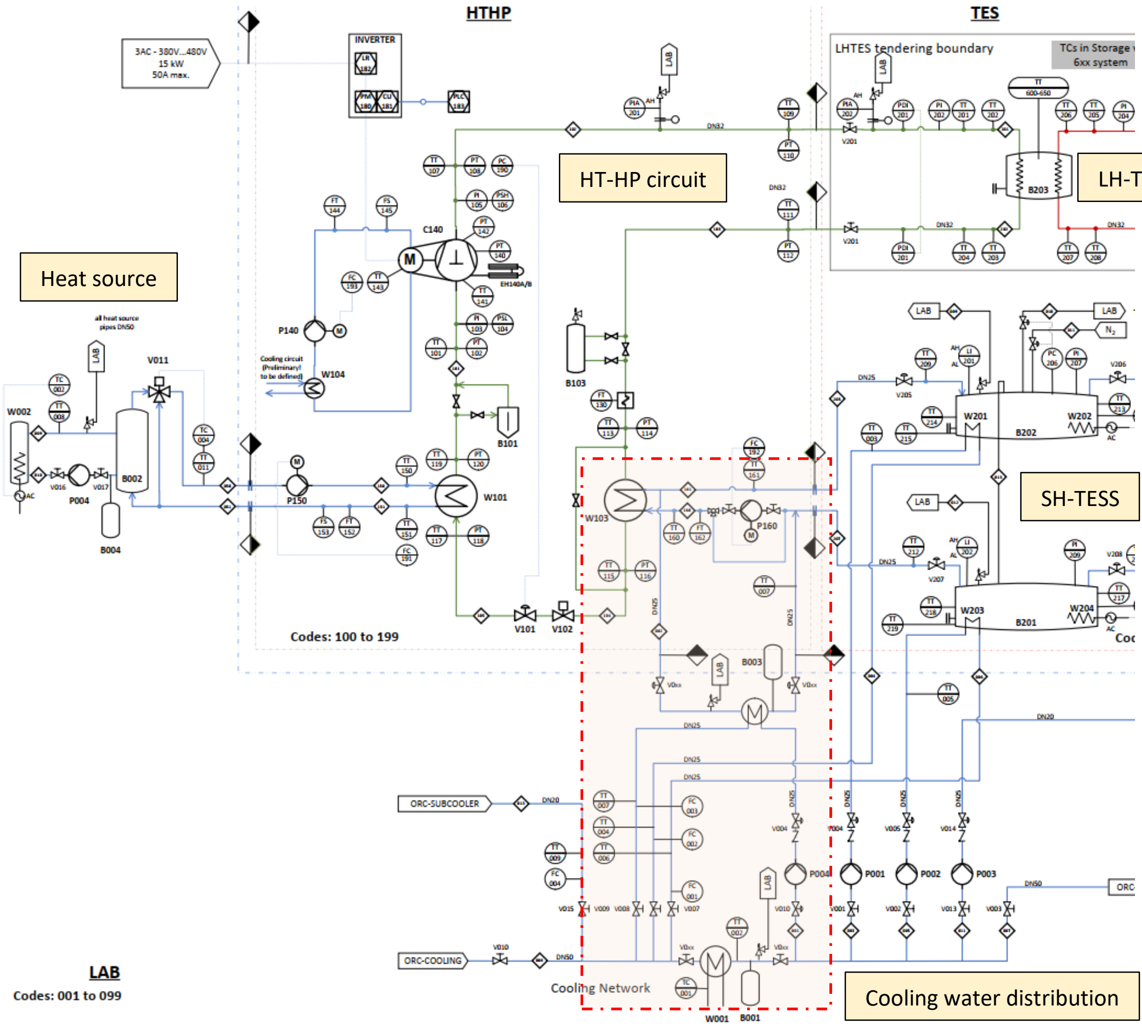

Figure 12: Excerpt from the P&ID containing HT-HP circuit, HT-TESS, heat source and cooling water distribution

At the laboratory level, two control processes are relevant during charging. Firstly, water at a constant flow temperature must be fed from the heat source to the evaporator W101 of the HT-HP. For this purpose, the buffer tank B002 must be continuously charged to a specific temperature by the electric flow heater W002. The three-way valve V011 mixes hot water from the buffer tank and return water from the evaporator to achieve the required flow temperature. Both the set point for the buffer tank temperature and the flow temperature at the evaporator inlet can be adjusted in the SCADA. The temperature difference at the water side of evaporator results from the mass flow rate in the water circuit, which is controlled by the speed of the pump P150.

Secondly, the operation of the SH-TESS must be controlled. During charging, water is pumped from the cold tank B201 to the hot tank B202 by means of pump P160. In the subcooler W103 of the HT-HP, thermal energy is transferred from the refrigerant to the water circuit, which leads to a temperature increase. The decisive control variable is the difference between the refrigerant temperature at the inlet and the water temperature at the outlet of the subcooler. The temperature difference is controlled by the mass flow rate on the water side, resulting from the corresponding pump speed. Further control variables are the water level and the pressure in both storage tanks. The water level is detected by radar sensors. Once the minimum or maximum level is reached, the shutdown procedure for the HT-HP will be initialized. In the case that the hot tank reaches the maximum water level before the LH-TES is fully charged, an additional control option is available. In order to maintain the charging process, the SH-TESS can be decoupled from the subcooler using the valves V205 and V207. The thermal energy is then dissipated via an intermediate circuit (marked by the red dotted line in Figure 12) directly to the cooling water network. To keep the pressure above the saturation pressure and to compensate volume changes due to varying water levels, the storage tanks are equipped with a nitrogen pressure control system. Both the pressure retaining valve and the release valve are mechanically controlled.

Discharging process

In this process, the HT-TESS is used to drive the ORC under various operating conditions. Figure 13 shows an excerpt from the P&ID containing the LH-TES unit, SH-TESS, ORC circuit and temperature-controlled heat sink. The components in the refrigerant circuit (red) such as expander E301 or the feed pump P303 as well as pump P301 and P302 in the water circuits are controlled by the ORC control system. The laboratory Siemens PLC controls the components of the heat sink. Corresponding set points are entered or adjusted in the SCADA.

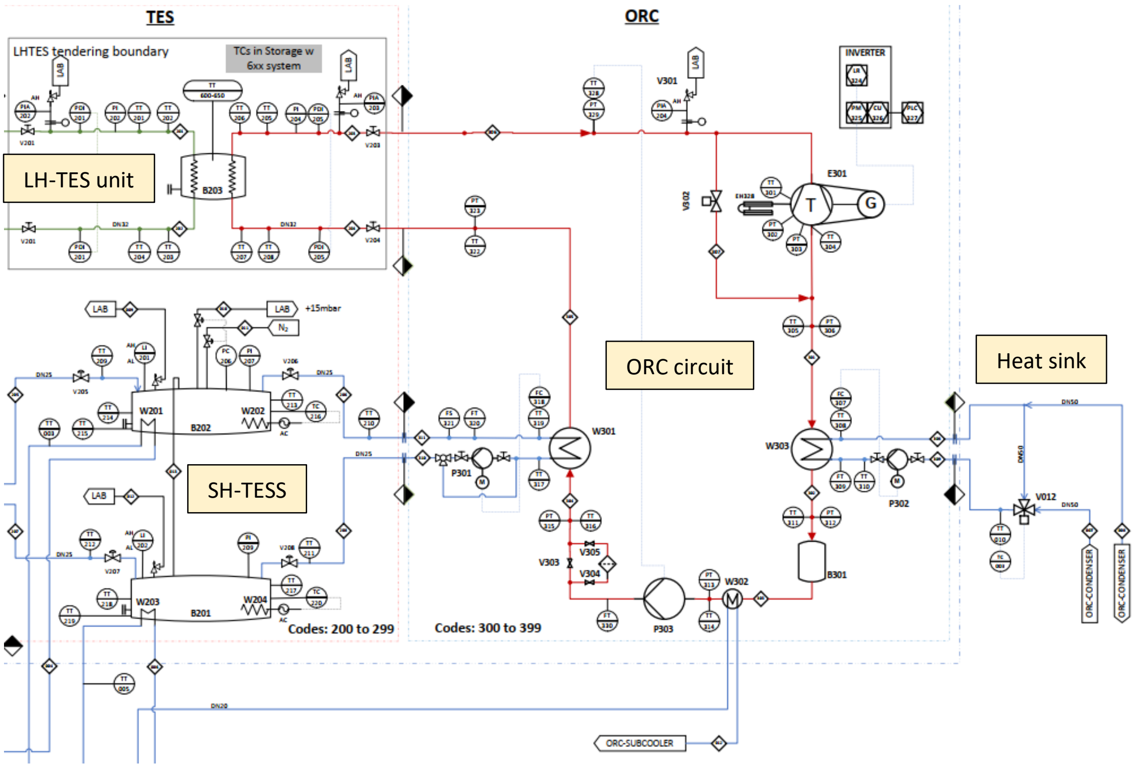

Figure 13: Except from the P&ID containing HT-TESS, ORC circuit and heat sink

At the laboratory level, three control processes are relevant during the discharging process. Firstly, water at constant flow temperature must be fed from the heat sink to the condenser W303 of the ORC. For this purpose, the three-way valve V012 mixes cold water from the cooling water distribution and return water from the condenser to achieve the required flow temperature. The flow temperature at the condenser inlet can be adjusted in the SCADA. The temperature difference at the water side of the condenser results from the mass flow rate in the water circuit, which is controlled by the speed of the pump P302.

Secondly, a specific mass flow of cooling water at constant flow temperature must be supplied to the subcooler W302.

Lastly, the operation of the SH-TESS must be controlled during discharging. This is done similarly to the charging process. Thereby, water is pumped from the hot tank B202 to the cold tank B201 by means of pump P301. In the preheater W301 of the ORC, thermal energy is transferred from the water circuit to the refrigerant to reach a flow temperature slightly below the saturation point. This is controlled by the corresponding speed of the pumps in the refrigerant and water circuits of the preheater. The control of water level and tank pressure is analog to the one described for the charging process.

System start-up

In addition to the charging and discharging processes, control strategies for the system start-up were also developed by the partners of WP3 and WP5. This mainly concerns the first commissioning of the overall laboratory CHEST system or the initial start-up after maintenance and repairs. The discussions resulted in three variants, which were considered in the manufacturing and installation of the prototypes. Additional variants are still being discussed and further analysis will determine which variant will be used in different situations.

Variant 1 requires an additional condenser to be connected in parallel with the LH-TES unit, as shown in Figure 14. Initially, the entire refrigerant mass flow is fed through the condenser. Thus, the HT-HP can be started up under defined conditions. Once a stable operating point is reached, the three-way valve is gradually opened to start heating the storage material in the LH-TES unit. After the preheating phase, the condenser is decoupled and the charging process can be started as previously described.

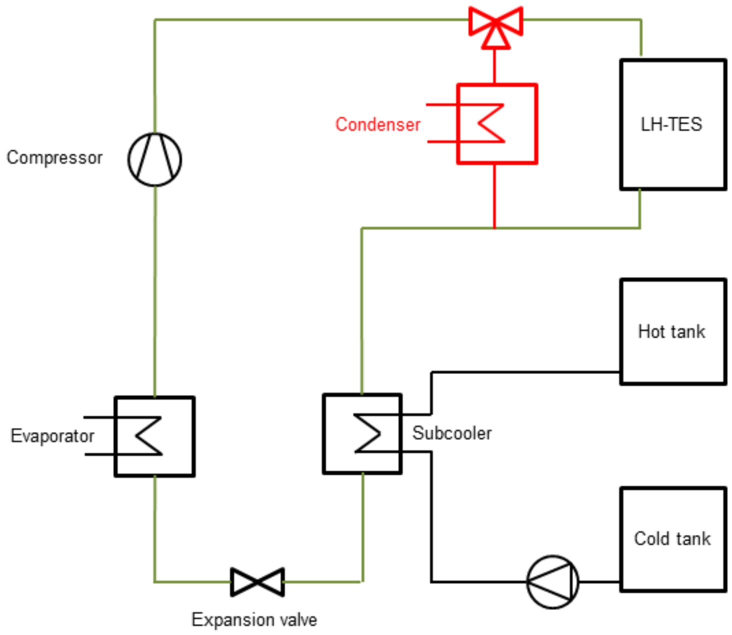

Figure 14: Schematic of the HT-HP circuit with additional condenser

Variant 2 comprises the installation of electrical trace heating on the LH-TES shell, marked by the yellow area in Figure 15. Thus, the preheating process can be supported and the heat losses during downtimes can be reduced.

Variant 3 offers an additional option to preheat the storage material in the LH-TES unit. For this purpose, the DLR laboratory steam infrastructure for organic fluids ProSTEAM (klein) will be connected to the HT-HP circuit, as shown in Figure 15. Thus, steam from a selected refrigerant can be generated under arbitrary conditions and supplied for preheating the PCM. During this process, the HT-HP is in preconditioning mode. After the preheating phase, ProSteam (klein) is decoupled by the valves marked in red and the charging process can be started as previously described.

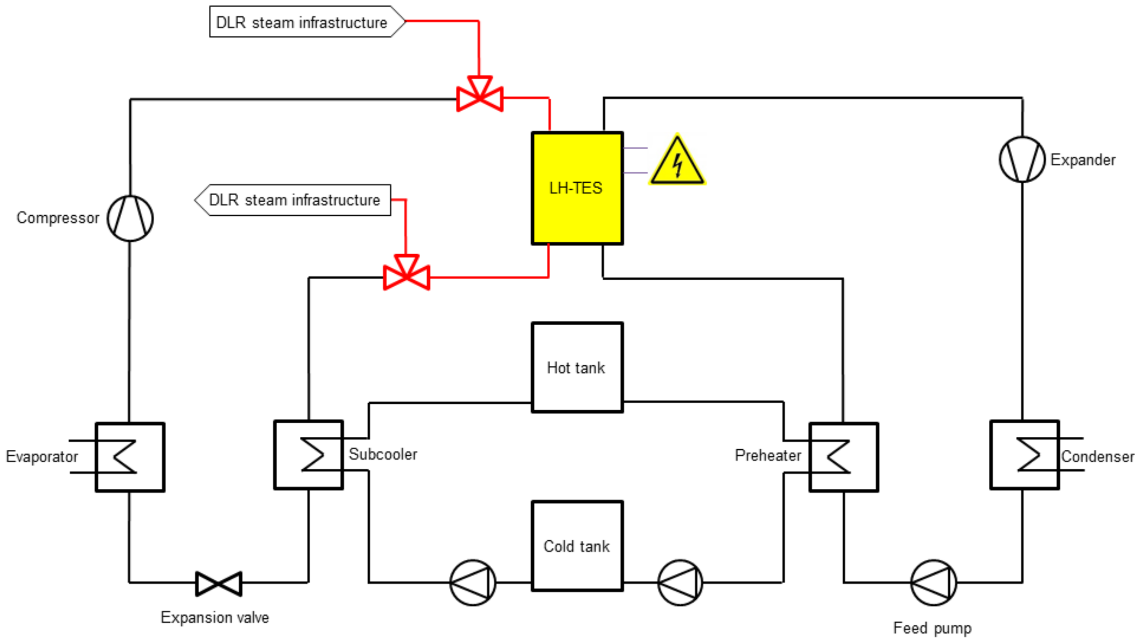

Figure 15: Schematic of the laboratory CHEST system with electrical trace heating on the LH-TES shell and connection to the DLR steam infrastructure for organic fluids

Conditioning of the SH-TESS between the experiments

Defined initial conditions are required to obtain reproducible results from the experiments. If the water temperature in the SH-TES tanks differs between the experiments, the water must be heated or cooled until defined initial conditions are reached.

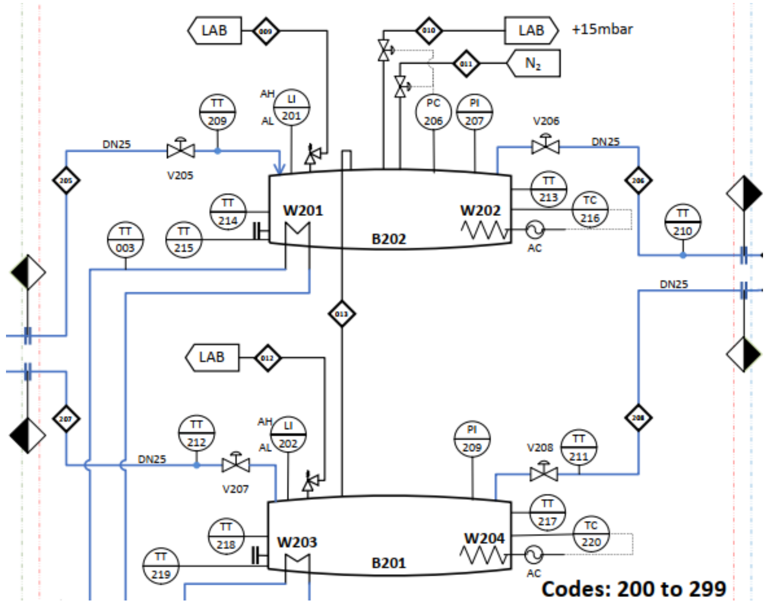

Figure 16: Except from the P&ID with the SH-TESS

Therefore each tank is equipped with an electric immersion heater (W202, W204) and an internal heat exchanger (W201, W203), which is connected to the cooling water distribution, as shown in Figure 16. The corresponding set points for heating and cooling can be adjusted independently in the SCADA.

2.4.4. Current status of task 5.1.3

The basic control architecture of the data acquisition and control system was developed, and control variables are defined. The common document is now being finalized by the partners of WP3 and WP5. Currently, the components for laboratory PLC and SCADA have been purchased and the control systems for HT-HP and ORC are in the manufacturing phase. Thus, the preparation for the installation of the data acquisition and control system is largely completed. However, some remaining work in task 5.1.3 can only be done once the manufacturing phase, testing and installation of the prototypes has been completed.

2.5. System layout and pipe connections

The objective of task 5.1.4 is the planning of the system layout and the pipe connections between the components of the laboratory CHEST system. In order to determine the optimal arrangement with regard to the laboratory infrastructure and the applicable safety regulations, a three-dimensional drawing of the laboratory H003 with the main components was developed. A preliminary draft of the planned system layout is given in Figure 17. Some of the prototypes are currently still in the manufacturing process and are thus depicted with placeholders.

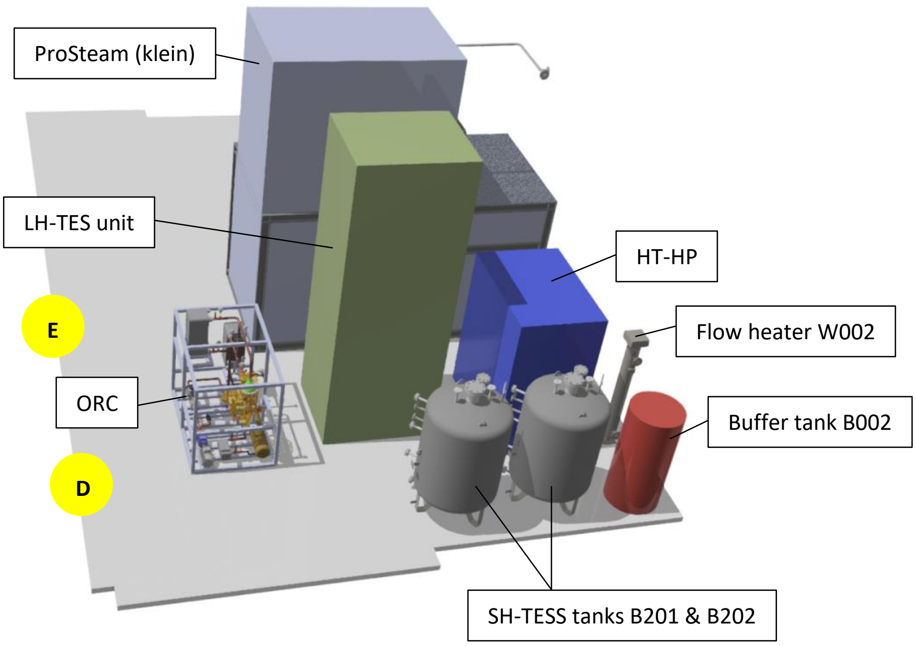

Figure 17: Preliminary draft of the laboratory CHEST system layout

The HT-HP is located on the right side, because the electricity supply and the heat source are there. The main components of the heat source are the electric flow heater W002 and the buffer tank B002. The HT-TESS, consisting of the LH-TES unit and the SH-TESS, is positioned in the middle of the test rig, in accordance to the P&ID. The electricity feed-in point for the ORC and the main connection to the cooling water network are marked by the letters D and E, respectively. To minimize the installation effort, the ORC is placed on the left side. The laboratory steam infrastructure for organic fluids ProSTEAM (klein), which is used for filling the PCM into the LH-TES unit and for preliminary testing, is located in the rear area of the CHEST system. This arrangement also considers the required distances for maintenance and repairs as well as appropriate escape routes.

In the next step, the placeholders are going to be replaced by the final 3D drawings of the individual prototypes and the layout will be adjusted as necessary. This can be done as soon as manufacturing process is completed. Once the final arrangement is defined, the pipework will be integrated into the 3D plan. The planning of the required pipe diameters and the design of components such as pumps or control valves has already been carried out.

2.6. Heat source and heat sink

Task 5.1.5 comprises the design and installation of the temperature-controlled heat source and heat sink. The heat source provides precisely controlled hot water as the heat transfer fluid to supply thermal energy to the evaporator of the HT-HP. The heat sink is used to cool the ORC's condenser. All components of the heat source and heat sink are controlled by the laboratory PLC and relevant set points can be adjusted in the SCADA.

Heat source

The electrical flow heater W002, depicted in Figure 18, transfers thermal energy to the primary water circuit in a heat output range between 1 and 100 kW_{th}. It is equipped with a primary PID-temperature controller to maintain the outlet temperature of the flow heater at the selected temperature with a high accuracy (of less than 1 K). As the mass flow rates of the primary and the secondary circuits are different, a hydraulic separator (B002) is required to decouple both streams. A membrane expansion vessel (B004) compensates the temperature dependent changes of the specific volume of the water inventory.

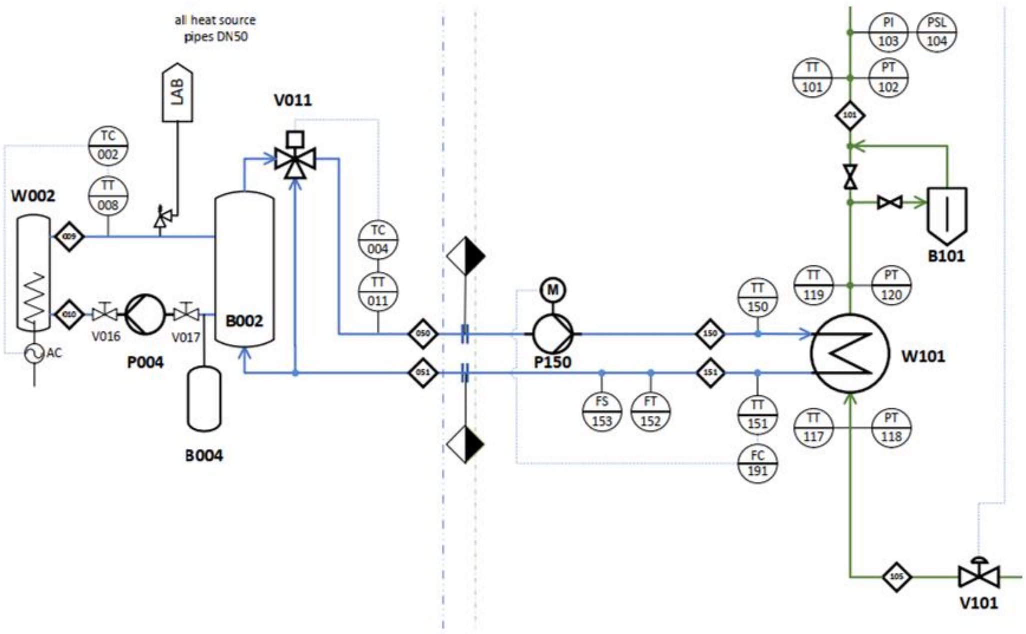

Figure 18: Schematic of the temperature-controlled heat source

To further increase the dynamic control stability of the outlet temperature T011, the hot feed stream from B002 is mixed with the cold return stream from the HT-HP by the three-way mixing valve V011. The valve has a linear characteristic and is equipped with a pneumatic actuator to ensure short positioning times. Figure 19 shows the resulting mixing temperature as a function of the relative mass flow of the hot stream. Due to the linear characteristic of the valve, the small increments of the actuator and the relatively small temperature difference, hot stream mass flow changes of 10 % result in a temperature change of 1 K at the outlet of the valve. Thus, the combination of the PID-flow heater controller and the fine control of the mixing valve will ensure a high accuracy of the outlet temperature even in transitional operating states.

An overview of the heat source specifications is given in Table 6.

Table 6: Technical specifications of the temperature-controlled heat source

Description	Unit	Value
Heat source outlet temperature	°C	40-98
Thermal output	kW	1-100
Temperature difference between in and outlet	K	5
Pipe dimensions	DN	50
Nominal pressure	PN	6

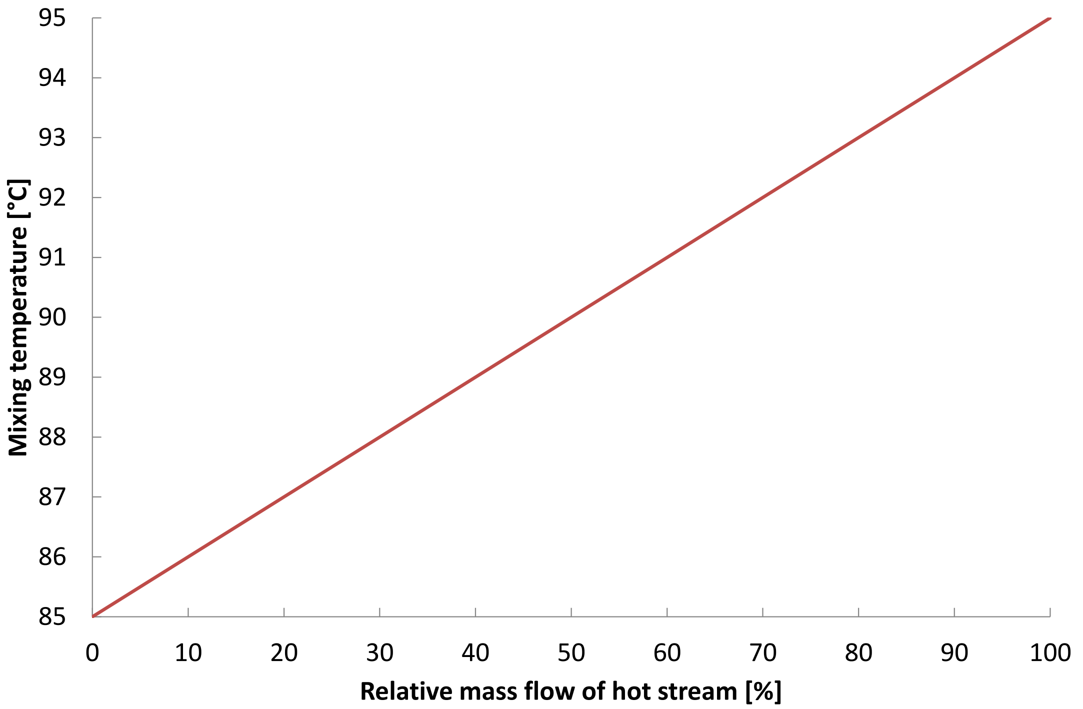

Figure 19: Valve characteristic and resulting mixing temperature of V011

Heat sink

The ORC's condenser W303 is cooled by the laboratory cooling water network. The feed stream from the laboratory cooling water network is maintained at approximately 20 °C. To control the actual cooling water inlet temperature T010, a fraction of the return stream is mixed with the feed stream at the three-way valve V012. The valve also has a linear characteristic as well as a pneumatic actuator with position controller. The corresponding valve characteristic is shown in Figure 21. Changes of 10 % of the cold stream mass flow result in 1 K temperature change of the mixed stream. Thus, similar to the heat source case, the mixing temperature can be very finely controlled.

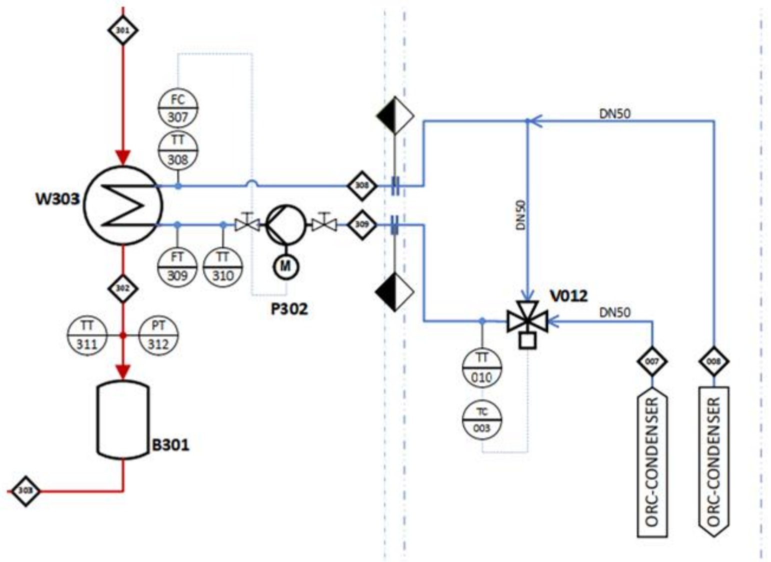

Figure 20: Schematic of the temperature-controlled heat sink

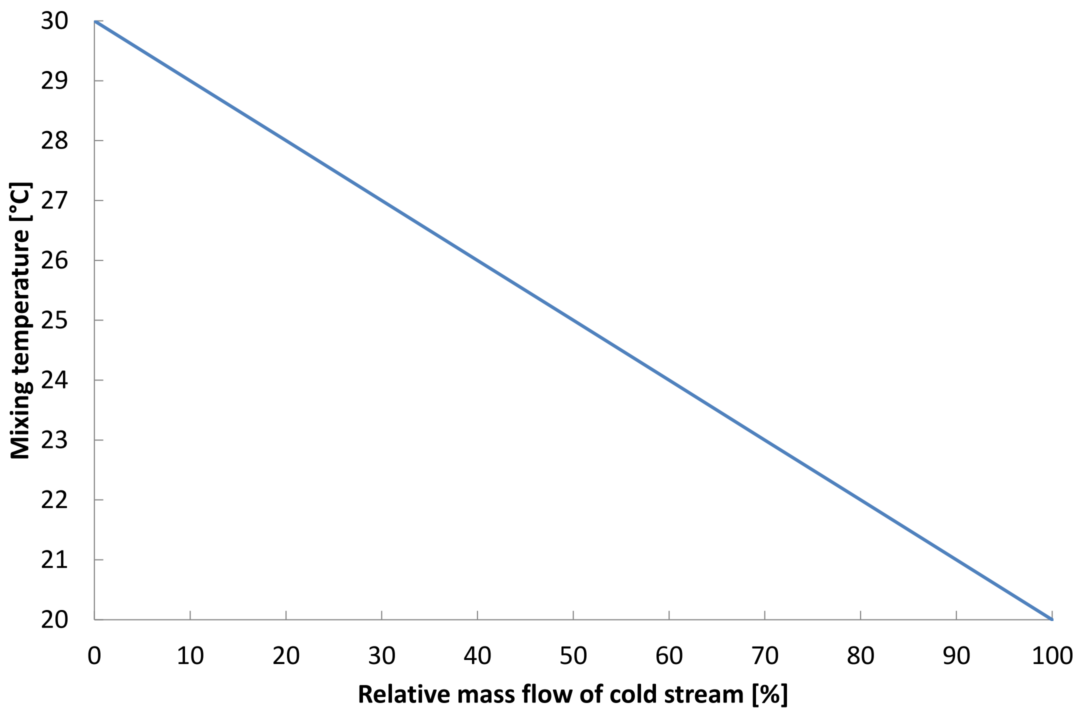

Figure 21: Valve characteristic and resulting mixing temperature of V012

The heat sink specifications are given in Table 7.

Table 7: Technical specifications of the temperature-controlled heat sink

Description	Unit	Value
Heat sink inlet temperature	°C	20-50
Thermal output	kW	100
Temperature difference between in and outlet	K	5
Pipe dimensions	DN	50
Nominal pressure	PN	6

The components of the temperature-controlled heat source and heat sink have been delivered and are ready for the final assembly. In order to improve the workflows in the laboratory, the installation of these components will be carried out in parallel to the installation of the individual prototypes in task 5.2.

2.7. Preliminary installation of the HT-TESS

As the available space in the laboratory is limited, an installation plan was developed to ensure a lean installation process and to avoid unnecessary delays. The installation of the laboratory CHEST system will begin with the LH-TES unit as soon as its manufacturing process is completed. Due to the height of the LH-TES and the dimensions of the laboratory door, it has to be brought into the laboratory horizontally and subsequently turned vertically inside the laboratory. This requires a certain amount of clearance, which would be obstructed by other large components such as the SH-TESS tanks. Therefore, the installation of the SH-TESS is scheduled after the installation of the HT-HP, the ORC and the heat source. On-site storage areas close to the laboratory are available and prepared.

3. Achievements

The main achievements of T5.1 are summarized in this section.

In order to provide the required space for the installation of the overall CHEST system, existing test rigs as well as unused infrastructure were disassembled and removed from the laboratory. Now, an area of approximately 50 m² is available for the assembly of the components in task 5.2. The main power supply, the electrical feed-in point for the ORC and the connections to the cooling water network were also prepared. This included an evaluation of the available cooling capacity to ensure that the various operating modes of the laboratory CHEST system could be tested. The results of this evaluation indicated that the available cooling capacity is sufficient.

In addition to the modern basic safety equipment, an emergency shower, an exhaust air system and a blow-out line for the prototype's safety valves were installed in the laboratory. Based on the material safety data sheets of the refrigerants used in the laboratory CHEST system, a risk assessment was carried out and operating instructions were created. As both substances are non-flammable, only measures to prevent direct contact and inhalation need to be taken. Appropriate safety precautions have been taken in this regard.

The control architecture for the laboratory CHEST system was developed and control variables were defined. The HT-HP and the ORC are controlled by individual control systems. The individual controllers will be connected to a superordinate SCADA system, which will be used for the control of the HT-TESS and the laboratory infrastructure as well as for a real-time visualization of the system operation, to change controller set points and for data acquisition. In order to use a common nomenclature for data acquisition, and to have all information in one place, a common table has been created. This table is a living document and will be continuously updated by the partners from WP3 and WP5 according to the progress of the prototype development and manufacturing. In order to operate the laboratory CHEST system, basic control strategies were developed and discussed among the partners involved. This comprises strategies required for the charging and discharging processes, system start-up and system's conditioning between the experiments. The preparation for the installation of the data acquisition and control system is largely completed. However, some remaining work can only be done once the manufacturing phase, testing and installation of the prototypes has been completed.

Under consideration of the laboratory infrastructure and the applicable safety regulations, a preliminary layout for the CHEST system was defined and a three-dimensional plan of laboratory H003 with the corresponding arrangement of the components was developed. Once the manufacturing process of the individual prototypes is completed, the final layout can be determined and the piping will be integrated into the 3D plan. The planning of the required pipe diameters and the design of components such as pumps or control valves has already been carried out.

The temperature-controlled heat source and heat sink have been designed with regard to the system requirements defined during the development of the prototypes in WP3. All components have already been delivered and are ready for the final assembly.

An installation plan was developed to ensure a lean installation process and to avoid unnecessary delays. The installation of the laboratory CHEST system will begin with the LH-TES unit as soon as its manufacturing process is completed, which is expected in June 2020.

4. Conclusions

With the achievements described in section 3, the laboratory was prepared for the installation and commissioning of the CHEST system. The work enabled that a complete assembly of all prototypes is feasible in the designated premises, including connection to the laboratory infrastructure and development of safety systems required for system operation. Relevant synergies between WP3 and WP5 were identified and utilized. These included the development of the control architecture and suitable control strategies. Dedicated visits to the partners enabled the development of a better understanding of the HT-HP and ORC operation and integration, as well as the clarification of the interfaces between the prototypes. These synergies are crucial for further progress in WP5.

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Annex

A.1. Laboratory CHEST system P&ID version 4.5