Low valued energy sources UPgrading for buildings and industry uses

LowUP Validation and upgrading recommendations report

Deliverable D4.17

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About LowUP

LowUp – Low valued energy sources UPgrading for buildings and industry uses – is developing efficient alternatives to supply heating and cooling for building and industries, based on the use of renewable free energy and heat recovery from non-valuated residual energy sources that are currently wasted. As a result, these technologies will contribute to reducing significantly CO_2 emissions and primary energy consumption, and increasing the energy efficiency in buildings.

Led by the Spanish firm ACCIONA, the LowUp project gathers 13 partners (3 large companies, 3 research and technology organisations and 7 SMEs) from 7 European countries. During 48 months, the consortium will develop efficient alternatives to supply heating and cooling for buildings and industries based on renewable free energy as well as non-valuated wasted thermal sources:

- 3 technologies will be developed and demonstrated: one heating and one cooling system for buildings, and one heat recovery system for industrial processes.
- The systems will be demonstrated at 4 demo sites: A Pilot Office building in Seville (Acciona Construccion, Spain), a Waste Water Treatment plant in Madrid (Canal de Isabel II & Acciona Water), a Pulp and Paper mill in Setubal (Portugal, The Navigator Company) and a Student Hall in Badajoz (Spain, University of Extremadura).

For more information visit: www.lowup-h2020.eu

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Executive Summary

This report (D4.17 "LowUP Validation and upgrading recommendations report") has been elaborated within the LowUP Project (GA #723930) and provides a compilation of conclusions, technology validation and upgrade recommendations obtained in the framework of Task 4.6. In the elaboration of this document has contributed all the technological partners of the project, either the technological centres, the systems integrators or the manufacturers itself. Each partner has provided their designs for the LowUp project, their measurements and particular conclusions about the application of the systems. The manufacturers also provided the recommendations they take in order to achieve next TRL for their systems on the way to the market.

In this task, it is reviewed system by system the three LowUp solutions (Solution 1: Heat LowUp, Solution 2: Cool LowUp and Solution 3: HP LowUp) in order to validate its adequacy for its purpose and to collect the next steps to be given. For each system it is collected the measurements of the performance of the equipment, the sensors selected for the measurement and where are they placed, and how the measurements are defined as Key Performance Indicators (KPI) for each system.

The validation of the systems vindicates the relevance of that systems in the frame of the market existing solutions, and their contribution to the circular economy paradigm, and decarbonization of climatization and industrial sectors.

Keywords

Validation, Conclusions, TRL, Technology development, Systems application

List of acronyms and abbreviations

AHU	Air Handling Unit
BMS	Building Monitoring System
COP	Coefficient of Performance
EVA	Ethylene-vinyl acetate
HP	Heat Pump
HSR	Heat System Recovery
HWHR	Hybrid Waste Heat Recovery System
IAQ	Indoor Air Quality
KPI	Key Performance Indicator
PCM	Phase Change Material
PET	Polyethylene Terephthalate
PLC	Programmable Logic Controller
PV	Solar Photovoltaic
PVT	Solar Photovoltaic & Thermal
P&ID	Piping and Instrumentation Diagram
RCR	Acronym of the original design of the self-cleaning rotating exchanger, first patented by POZZI many years ago, taken as a base point for the LowUP project. On this design the innovations and the specific original work is being carried out to render it more efficient and suitable for the LowUP task.
RHeX	Rotating Heat Exchanger (from Pozzi)

RMSE Root Mean Square Error

SCADA Supervisory Control and Data Acquisition

SWHR Sewage Water Heat Recovery

WHR Waste Heat Recovery

WWTP Waste Water Treatment Plant

1 Introduction

The scope of task 4.6 is to research for potential improvements of the prototype systems, leading to an optimization of the whole systems. Validation of the prototype systems developed in previous tasks will be performed, for each component of the different solutions (Heat-LowUP, Cool-LowUP and HP-LowUP). In case of successful validation, these methodologies could be developed at higher TRLs, before being replicated and implemented for different commercial scale scenarios: emplacement, climate etc., in order to use them throughout Europe.

For the execution of this task there has been contribution from all the partners of the project, either the technological centres, the systems integrators and the manufacturers itself.

1.1 Motivation and objectives

The first objective of Task 4.6 is to validate the application of the LowUp technologies installed at the pilot sites for all the three LowUp solutions: Heat-LowUp, Cool-LowUp and HP-LowUp. To do so, their operation has to be monitored and measured in a standardized procedure for all of them, so they can be comparable and evaluated with the same criteria.

The second of objective of Task 4.6 is to stablish the next steps towards the next TRL for each systems with regards to make the development of LowUp project to reach the market and cause an impact in the waste heat recovery sector.

The information collected for each system of the LowUp solutions is:

1- Sensor selection and physical emplacement
2- Data acquisition of the different characteristic parameters
3- Monitoring and recording of the validation parameters
4- KPI monitoring
5- Results validation of the prototype system installed in a real emplacement
6- Next steps to reach next TRL

1.2 Relation to other project tasks

This deliverable (D4.17) is comprised of Task T4.6 in WP4. This task is related to the three technical core work packages. It collects information from the design and study of the climatization solutions (1 and 2) from WP2, and the industrial heat solution (3) from WP3. In WP4, all the three solutions are projected, installed, started and operated. In order to extract conclusions of the operation results, and therefore validate the technologies, information from all tasks related to the information points detailed in the section above.

Moreover, next, Table 1 describes in more detail the relationships between the tasks reported in D4.17 and the rest of the project.

Table 1. LowUP tasks that will interact with results derived from D4.17

Task / WP	Relationship
WP2	Information from all the innovative systems of building climatization installed in WP2 is collected. In WP2 is carried out the design and study of the systems for Solution 1 and 2.

Task / WP	Relationship
WP3	Information from all the innovative systems of industrial heat installed in WP3 is collected. In WP3 is carried out the design and study of the systems for Solution 3.
WP4	Information related to design, installation and operation of the three LowUp solutions is collected.

2 Presentation of the system

A general approach is shown below, in which the three main systems with their correspondent elements are briefly explained. Three technologies were developed and demonstrated: one heating and one cooling system for buildings called Solution 1: Heat-LowUP and Solution 2: Cool-LowUP, and one heat recovery system for industrial processes Solution 3: HP-LowUP.

2.1 Solution 1: Heat-LowUP

- Purpose: Heating service for residential buildings using renewable sources
- Diagrams:

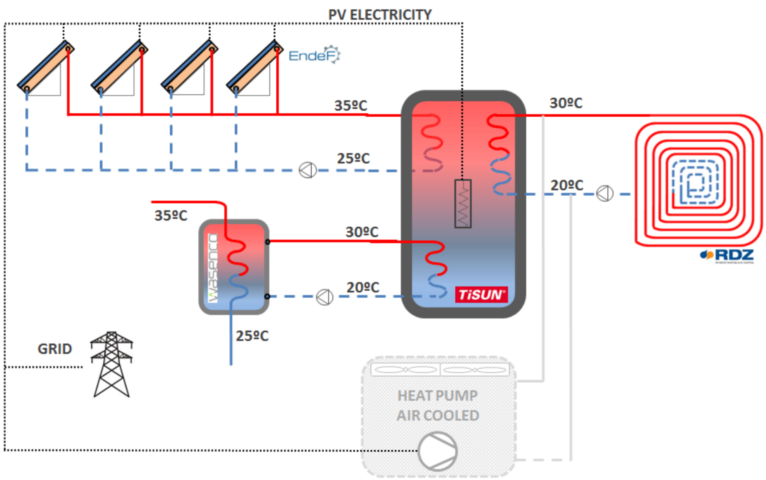


Figure 1: General diagram of the Heat-LowUP system

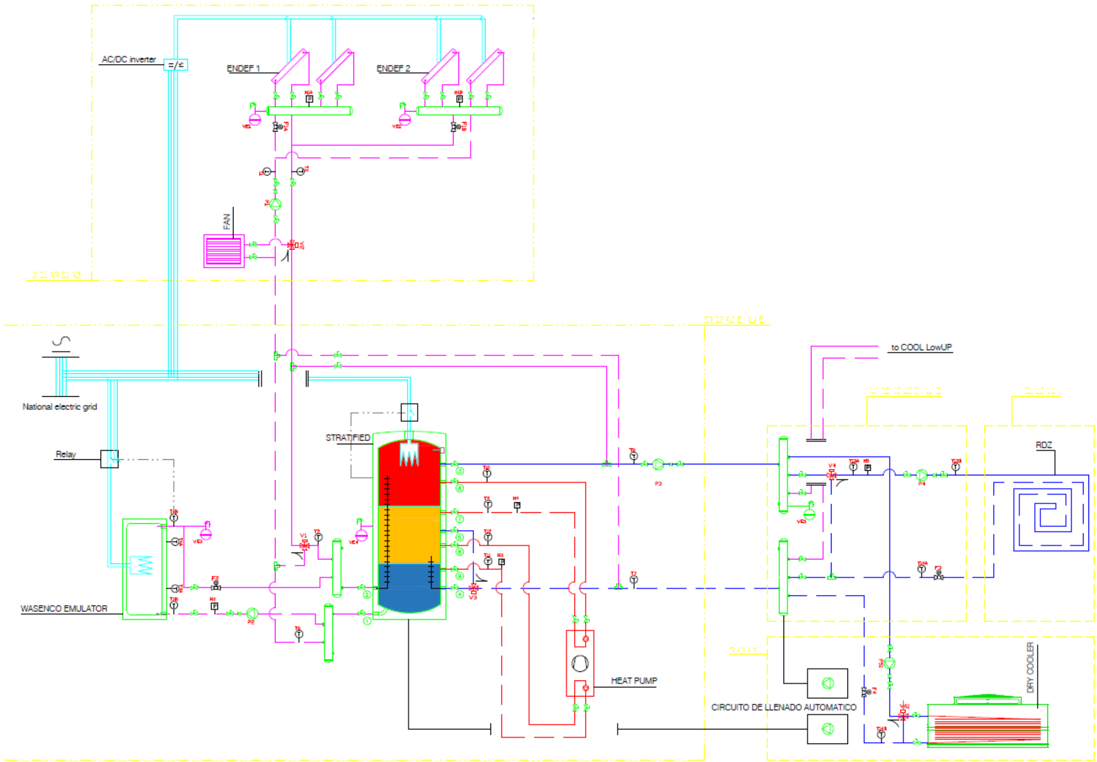


Figure 2: Detailed diagram of the Heat-LowUP system

- Description:

  Heat-LowUP constitutes a novel, effective and reliable heating system for application at new or refurbished buildings with centralized HVAC. It combines heat recovery technologies from low valued energy sources like renewable (solar thermal) and residual (sewage water), with low exergy heating terminals (water-based radiant surfaces).

  As shown in Figure 1**¡Error! No se encuentra el origen de la referencia.** and **¡Error! No se encuentra el origen de la referencia.**, a thermal recovery system is equipped in the PV panel, in order to ensure an efficient operation utilizing the dissipated heat. This heat is stored in the stratified tank, which collects thermal energy from different incomes. In turn, the necessary heat that will be used for the radiant floor to satisfy the thermal load of the building is obtained directly from this tank. Furthermore, the power generated in the PV module is used to heat the tank as well.

  The stratified tank is also fed by the waste heat produced in the sewage energy recovery system installed in the students residence of Badajoz. Consequently, this sewage heat is simulated in Seville through a thermal emulator, consisting of a water tank equipped with a Joule-effect electric resistance. The energy dissipation system, also called as dry cooler, allows to test different energy productions and works simultaneously with the radiant floor. If the energy stored is not sufficient to deal with the current building´s thermal loads, a heat pump is triggered as an auxiliary system.

- Components

  - Stratified Tank

- PV Module with Heat Recovery System from Dissipated Heat (ENDEF)
- Radiant Floor Heating System (RDZ)
- Heat recovery system from Waste Water (WASENCO)

2.2 Solution 2: Cool-LowUP

- Purpose: Cooling service for residential buildings using renewable sources
- Diagrams:

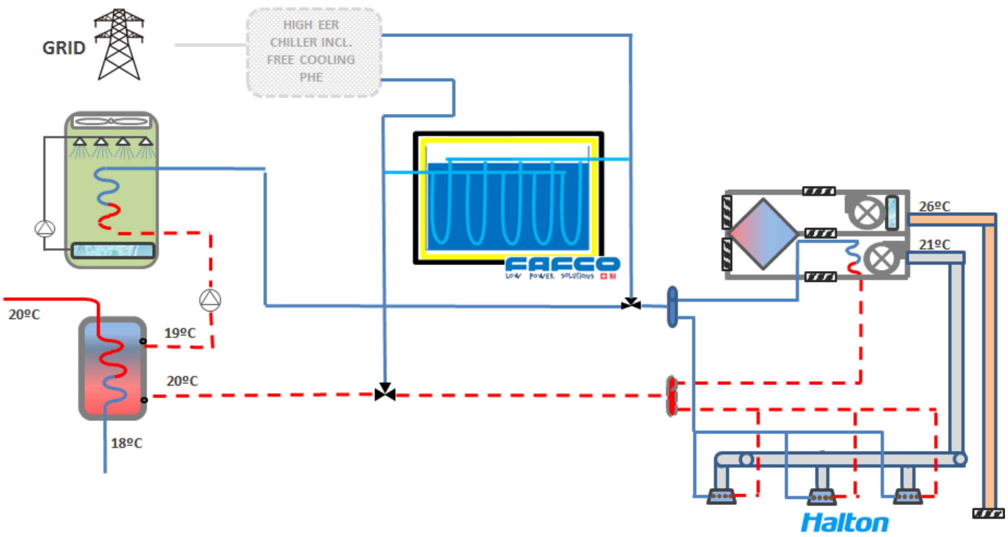


Figure 3: General diagram of the Cool-LowUP system

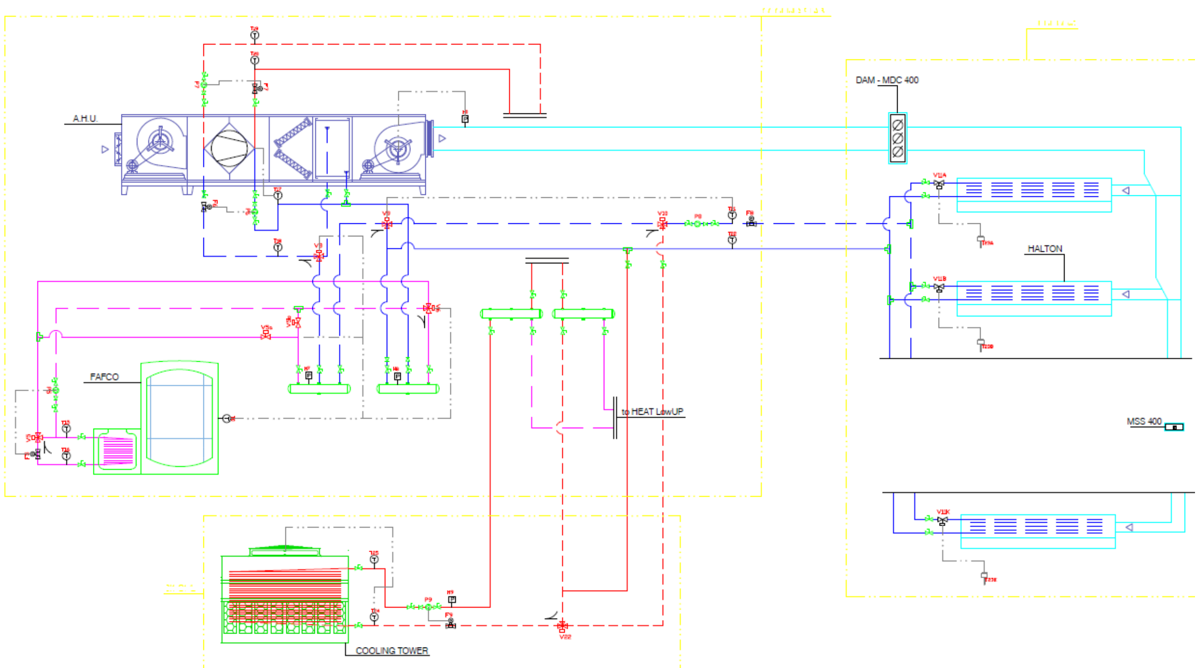


Figure 4: Detailed diagram of the Cool -LowUP system

- Description:

  Cool-LowUP constitute a novel, effective and reliable cooling system, with share of free renewable energy source of around 25% for application at new or refurbished buildings with centralized HVAC. It combines high-efficiency cooling generation equipment (based on WC chiller and cooling tower) taking advantage of low valued energy sources like ambient air, with low exergy cooling terminals like active chilled beams. These kind of constructions are able to operate with minimum ventilation flow and supply water temperatures of approx.. 18°C, in order to meet sensible cooling loads.

  Cool-LowUP pretends to overcome current limitations in cooling systems, such as poor COPs, by the introduction of improvements in several fronts: by using cooling terminal devices operating at higher temperature respect to actual technology and recovering cooling from environment instead of producing it via compression cycle (18/16°C instead of 7/12°C); by using PCMs (Phase Change Materials) to store cooling energy.

- Components
  - PCM Tank (FAFCO)
  - Chilled Beams

2.3 Solution 3: HP-LowUP

- Purpose: The HP-LowUP concept is based on an effective and reliable heat pump system, 100% thermal powered by residual low temperature energy sources (below 45°C), for application at industrial processes with temperatures up to 80°C.

- Diagrams:

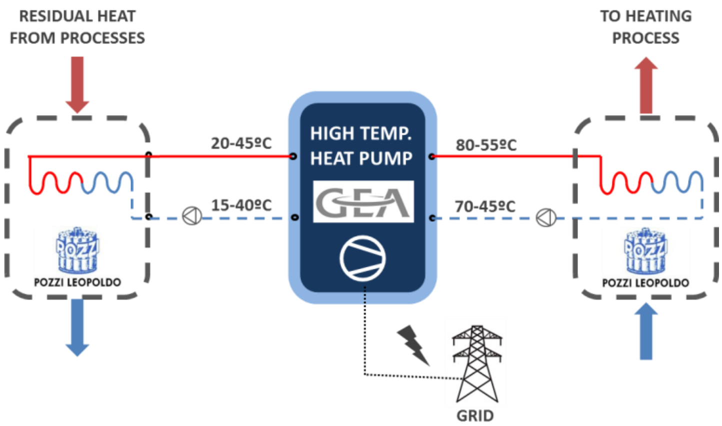


Figure 5: General diagram of the HP-LowUP system

- Description:

  Looking at the cold sink/evaporator side (Figure 5), GEA heat pump collects directly residual heat from sewage water and process waste heat (Case studies of the WWTP of Canal de Isabel II in Pinto (Spain), the Pulp & Paper industrial plant of Navigator in Setúbal (Portugal), and a possible application in the automotive factory of Ford in Almussafes (Spain), all of them described in deliverable D3.1), obtaining a low temperature range stream between 20 and 45°C. This is a low quality heat, but still usable for the system.

Concerning the hot sink/condenser side, it is possible to generate a certain temperature increment (between 10°C and 5°C) which is useful to increase the temperature of several heating processes related to all case studies. Both heat exchange operations are performed through the Heat exchangers developed by Pozzi (RHeX-Pozzi, more extensively described in Deliverable D3.2), being one of them a self-cleaning heat recovery system used in the cold sink of the heat pump.

Finally, the electrical work the heat pump needs to operate is directly fed from the power grid.

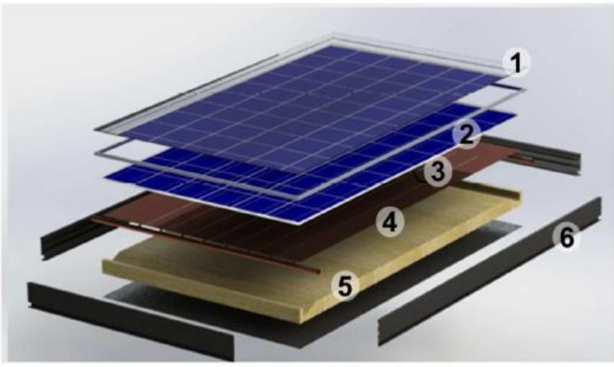
- Components:
  - HP-GEA (D 3.3)
  - RHeX-Pozzi (D 3.2)
  - Optimizer (D 3.5)
  - Maintenance (D 3.6)

3 Solution 1: Heat-LowUP

3.1 Component 1: PVT – ENDEF

The ENDEF´s PVT solar unit is a technology that joins together a thermal collector and a photovoltaic panel into one unique device. This kind of hybrid technology includes the main components of the other two units: the photovoltaic laminate and the heat-exchange absorber. The work developed by ENDEF involved the research of new material-configuration combinations that improve the PVT features without sacrificing the efficiency. The final objective is to develop an efficient hybrid PVT solar unit able to be integrated almost directly into low-exergy heating and cooling applications.

The design of this hybrid PVT solar collector includes different layers, typical of the common thermal collectors and photovoltaic panels found in the market. The mandatory components are the photovoltaic module and the heat-exchange absorber unit, which are placed one after the other in order to allow the heat transfer (Figure 6).



1. Frontal glass cover
2. PV laminate
3. EVA adhesive
4. Heat-absorber unit
5. Rock-wool insulation
6. Aluminum frame

Figure 6: Common PVT panel components

In the hybrid solar panel, the solar radiation projected on the panel is first absorbed by the PV layer which generates power. It is PV made from cells, commonly based on silicon (mono-Si, poly-Si), although other PV materials are gaining relevance in recent times, such us thin film technology or organic films. In order to ensure a correct performance of the PV part, the excess of heat produced in this layer has to be released to the thermal layer, also called the heat absorber unit. Both components must be merged to facilitate the heat transmission.

Inside the heat absorber unit there is a fluid (usually air or water) which absorbs the heat and transports it to the heat demand place. The absorber geometry and type of union within the PV module, are the main constructive factors that determine the thermal efficiency of the panel and therefore, the electrical performance of the PV module.

As a novelty in the common hybrid field, a phase change material is included into the PVT unit, which is able to store energy during the peak sun hours and release it when the sun disappears, redistributing the heat production and generating a more stable output while reducing the maximum operation temperature of the panel.

For the correct design and construction of this system, the following procedures have been carried out:

- For the heat absorber layer, a review and analysis of the different absorber design and options, in terms of viability, thermal conductivity, costs and other physical aspects such as weight, size or pressure, was done. Accordingly, three numerical steady state thermal simulations for three different materials were carried out:

- Metallic heat absorber, made of alloy steel
- Polymeric heat absorber, composed by a unique alveolar polycarbonate plaque
- Aluminium heat absorber, developed by CGA technology

The main terms considered for these analysis were the following:

- Fluid temperature
- Contour temperature
- Fluid velocity

- Concerning the PCM, three PVT hybrid systems, which are available in the market were numerically simulated, in order to determine the approximate thermal collector temperature under operation conditions. Thus, three configurations were considered:
  - PVT-0: no insulation layer
  - PVT-1: insulation on the back of the panel
  - PVT-2: insulation on both sides of the panel (front and back)

  The three PVT models were compared in terms of their maximum and minimum temperature, which is a required information to establish the right temperature range. It has been determined a T range between 45-50°C. Thus, assuming this value as a starting point, two PCMs are proposed to be used in the PVT prototypes:

  - The organic RT50, RT-LINE of Rubitherm® Technologies GmbH
  - The inorganic C48, ClimSEL™ line of Climator Sweden AB.
- The final action entails the manufacturing and testing of two selected models under different configurations. After all this process, the main characteristics of the final Hybrid PVT Solar panels chosen are shown as it follows:
  - Unglazed Roll-bond prototype
  - Type of PCM: C48
  - Hydraulic connection based on Tichelmann loop: 40 PVT panels to be installed (2 circuits: 20 PVT panels with PCM integrated and 20 PVT panels without PCM.
  - Electricity production: 270 Wp/panel
  - Electricity consumption: 1.5 kW
  - Special requirements for installing activities:
  - Available space without shadows.
  - Foundation able to support PVT weight.

Figure 7: Picture pf the final prototype of the solar field

The final devices were built by ENDEF and operated in Tecnalia installations. They constitute one of the main elements of the Heat-LowUP system for space heating of buildings, and are subject to testing and operation in the Pilot Office Building demo site of Acciona, in Seville.

Regarding to the final configuration and installation of the solar field, it is composed by a set of solar panels connected through a piping system, with its respective water pump and monitoring systems. Two solar fields (with and without PCM) have been installed in parallel for testing purposes and hydraulic balance; each field is composed by 20 panels in parallel, divided in rows of 5 units, as indicated by temperature lift calculated during engineering phase.

The final layout proposed by the manufacturer is shown as follows:

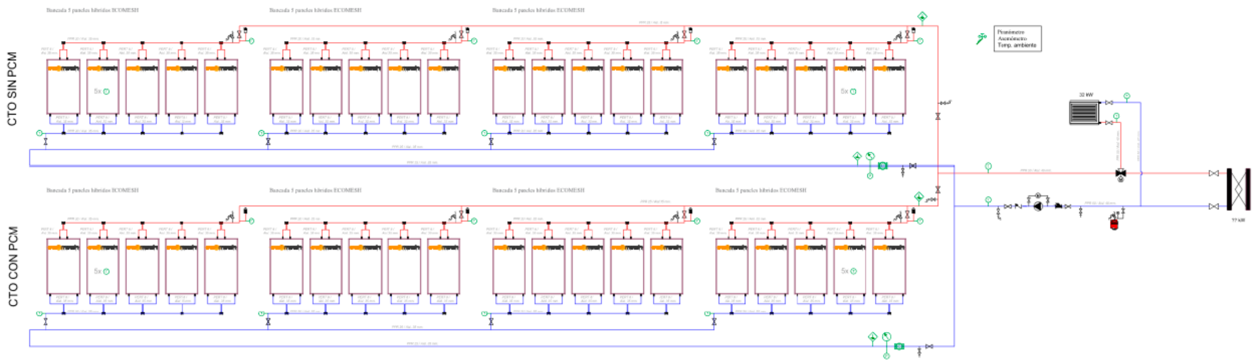


Figure 8: PV system layout

Figure 9: Heating system – Solar field with pumping station

The main specific features and operation aspects considered for this system are here explained (deliverable 2.11):

- PV/T fields: 40 PV/T panels in all were installed in Seville. These were distributed in two different fields connected to separate manifolds. One of the PV/T fields (20 panels) corresponds to units without PCM back layer, while the other (with the remaining 20 panels) incorporate 32 PCM packs per panel (i.e. 16 kg of PCM per panel distributed in 100x280 mm packs)
- PV/T electricity output: As it can be observed in the updated layout, for what concerns the energy management of the demonstration facility, the electricity output of the PV/T panels will be used to feed the electric resistances of the overall system when needed. However, the real potential in future operational buildings will be linked to either use as much electric energy as possible produced from the PV/T to feed internal electrical appliances or loads (self-consumption), or establish a net balance with the grid in order to contribute to economic savings from reduced electricity costs as well as to cleaner energy production through increased renewable share and distributed electricity generation. In this sense, for simulation purposes the overall electricity consumption for backup resistances connected to the stratified tank as well as the overall electricity production obtained from the PV/T field will be accounted for.

3.1.1 Sensor selection and physical emplacement

A general explanation about sensors, including their description and their operation, can be found in deliverable 2.9, section 5.3. Furthermore, Annex 2 presents the list of control variables and includes information about the type of signal and measurement range identified for all different sensors proposed for the demonstration. Concretely, for HEAT-LowUP and COOL LowUP solutions the most relevant sensors to be used are devoted to:

- Energy Monitoring,

  Mainly used to measure the energy consumption in building facilities and carry out further calculations (for instance, the COP of a heat pump), energy sensors are widely needed. The main measurements are: electricity, heating and cooling energy consumptions.

  For the first case, a wide catalogue is available, which allow the measurement of energy, power consumption, current consumption, voltage, phases, cos phi, etc.

  Concerning heating and cooling energy, there are several devices that allow the energy consumption measurement in two different ways: (i) some devices are able to calculate the consumed energy using the flow rate and two temperature sensors (inlet and outlet); (ii) others are only capable to measure the flow, obliging the user to calculate the energy consumption by other means.

- Weather Monitoring

  It is key for the development of the whole control and surveillance concept within the LowUP project. At high level, it will allow to integrate weather forecasts into the control algorithms and it will be able to support to evaluate fault detection rules, etc. At low level, weather information (particularly outdoor temperature conditions) is crucial to enable weather-compensated setpoint definitions (e.g. for the water supply temperature at the radiant floor system) and proper selection of operational modes (e.g. on/off of the cooling tower as a function of the outdoor wet-bulb temperature values).

For this kind of devices, there are several recommendations that can be mentioned:

- Fast update time (every 2,5 s)
- Electronic components should be housed in a weather-resistant shelter.
- Flexible powering of the console if available through a power adapter or corresponding batteries
- Wireless range up to 300 m outdoors, line of sight. The typical range through walls under most conditions is 60 to 120 m.
- Additional wireless repeaters for distances up to 2.7 km.

The LowUP demo site in Seville has a complete weather station, which is currently used for other projects and the management of the existing facilities

- Indoor Air Quality (IAQ) and Thermal Comfort

  IAQ depends on the concentration of contaminants within the indoor environment and is also related to the existence of odours, etc. Nevertheless, it is widely accepted that CO_2 concentration can be consistently representative of IAQ in most normal indoor environments (offices, etc.). The norm EN 13779 defines several classes for indoor air quality:

  Thermal comfort theory is also mentioned in deliverable 2.9, section 5.3.3 and depends of the so-called operative temperature, affected by 6 main parameters: air temperature, moisture content (humidity), radiant temperature, air velocity, human metabolism and clothing index. However, in practical situations within widely-extended indoor environments in residential and office buildings, thermal comfort conditions can be understood as the mix of at least 2 different effects linked to the air temperature and the humidity level.

  In the end, thermal comfort is also highly related both to physiological and psychological aspects which give rise to the subjective thermal perception or feeling of each individual.

  On the other hand, global thermal comfort depends of the so-called operative temperature which is affected by 6 main parameters: air temperature, moisture content (humidity), radiant temperature, air velocity, human metabolism and clothing index. However, in practical situations within widely-extended indoor environments in residential and office buildings, thermal comfort conditions can be understood as the mix of at least 2 different effects linked to the air temperature and the humidity level.

  However, despite all the previous concepts established, thermal comfort is also highly related to the subjective thermal perception or feeling of each individual. For this reason, being in comfort is not deterministic; it depends on the people being asked, and so, its analysis is addressed through statistical approaches.

  For these reasons, it is neither usual to have a control system based on operative temperature, but in wet bulb temperature sensors (in order to consider dry-bulb temperature and moisture). In this context one of the possible sensors which is able to measure relative Humidity, dry-bulb temperature and CO_2 concentration is the Thermokon WRF04 CO_2, which was suggested for its implementation in the LowUP project.

The three main sensor devices used for both HEAT-LowUP and COOL-LowUP solutions are explained in deliverable 4.6, section 2.3, as follows:

- Three phase electrical energy meter:
  The energy meter is used to measure and log consumption of electric devices fed by main electric cabinets. By this way, it is possible understanding real efficiency of entire system.
- Flow meter:

  The flow energy meter is used for several purposes:
  - Measure and log consumption of thermal devices fed by thermal units
  - Flow regulation of different pumps with variable speed driver.

  It is composed by a flow meter integrated with 2 temperature sensors installed on hot and cold pipes. Concretely, the MULTICAL® 403 model calculates the energy using the formula indicated in the EN 1434-1 standard, where the international temperature scale of 1990 (ITS-90) and the definition of 16-bar-pressure are used.

  Simplifying, the energy calculation is expressed as Energy = V x ΔΘ x k, with V as the volume of water supplied, ΔΘ as the measured temperature difference, and k as the thermal coefficient of water. The integrator calculates the energy in [Wh], which is subsequently converted into the selected measurement unit.
- Static pressure sensor:
  The PL-528 range of static pressure transmitters is suitable for use with liquids and non-aggressive gases compatible with the FPM. It is based on proven ceramic technology for exceptional performance speed and reliability.
- Temperature sensor

  The Weatherproof IP65 Housing model is the chosen device, which has a wide range of sensing element types, and stainless-steel probe. Immersion sensors are prepared for direct mounting into the PDCSY-TT-PO range of stainless-steel pockets.

Deepening into the solar field and its instrumentation installed, the control side of the equipment is composed by several pressure and temperature sensors, a VSD pump, flow meters and an electrical cabinet with PLC. Power and control wiring proceed from the local electrical cabinet and is connected to every component of the solar system. That cabinet needs to be installed spaced below for ventilation reasons and also to facilitate electrical connections. Next figure shows in detail how the connections and the electrical security components are disposed in the cabinet.

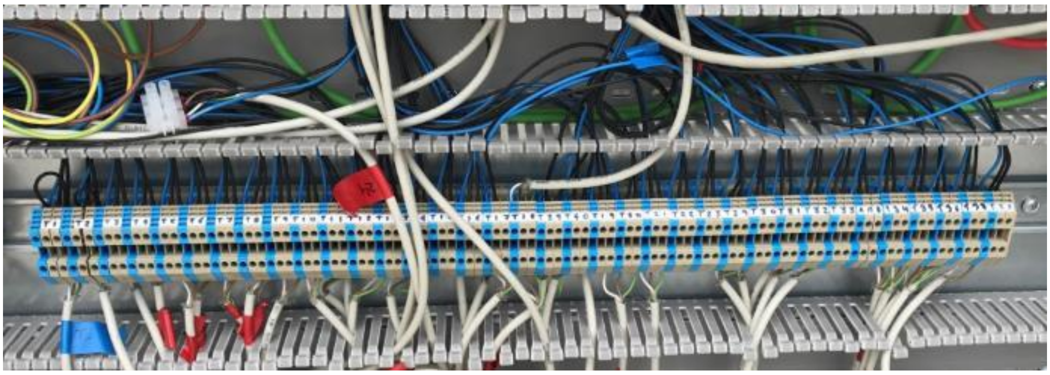


Figure 10. Electrical connections in solar field cabinet.

Figure 11. Control connections of local plc.

Concerning the hydronics, and with the aim of guaranteeing a correct and secure installation and operation of the pumps, the system has sensors distributed all over the equipment. Moreover, it was necessary to add some components like filters, isolating valves, pressure sensors, 2-way valves and correct hold-down devices. Several elements of the circuit are displayed through the following figures:

Figure 12. Detail of a pump installed in the solar field

In the next figures it is possible to see several sensors, regulation devices and components installed on the primary circuit of the thermal solar field.

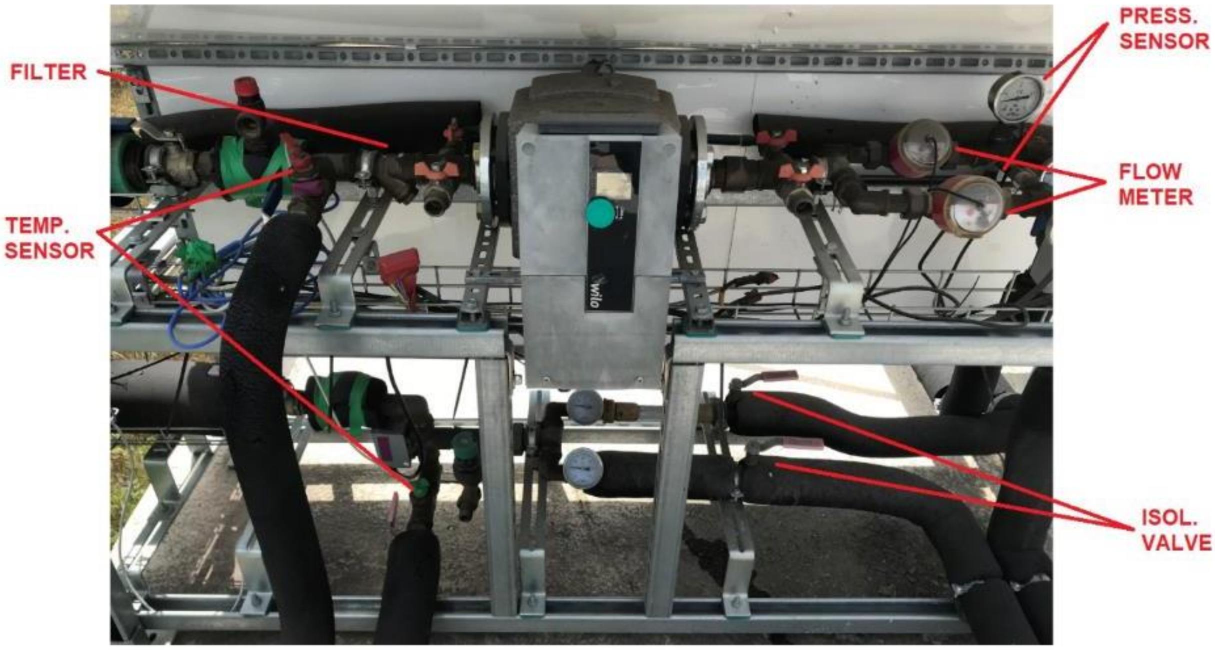


Figure 13. Solar pump station with regulating devices.

The Hydraulic side of the solar field is controlled by both Endef and LowUP PLCs. Endef PLC controls and regulates the operation of the pump (P1 in the diagram) with respect to the outcoming temperature under the required set point. The LowUP PLC regulates the access from the solar loop to the stratified tank through a 3 - ways valve (V1), in order to feed the tank only with the required temperature and not lower. Thereby, during the warm-up phase, the valve excludes the solar loop from the tank, while the pump circulates the water at fixed flow until achieving the desired temperature from the panels; once the temperature is achieved, the valve opens and the pump adjusts its speed according to the intensity of radiation and the set point temperature.

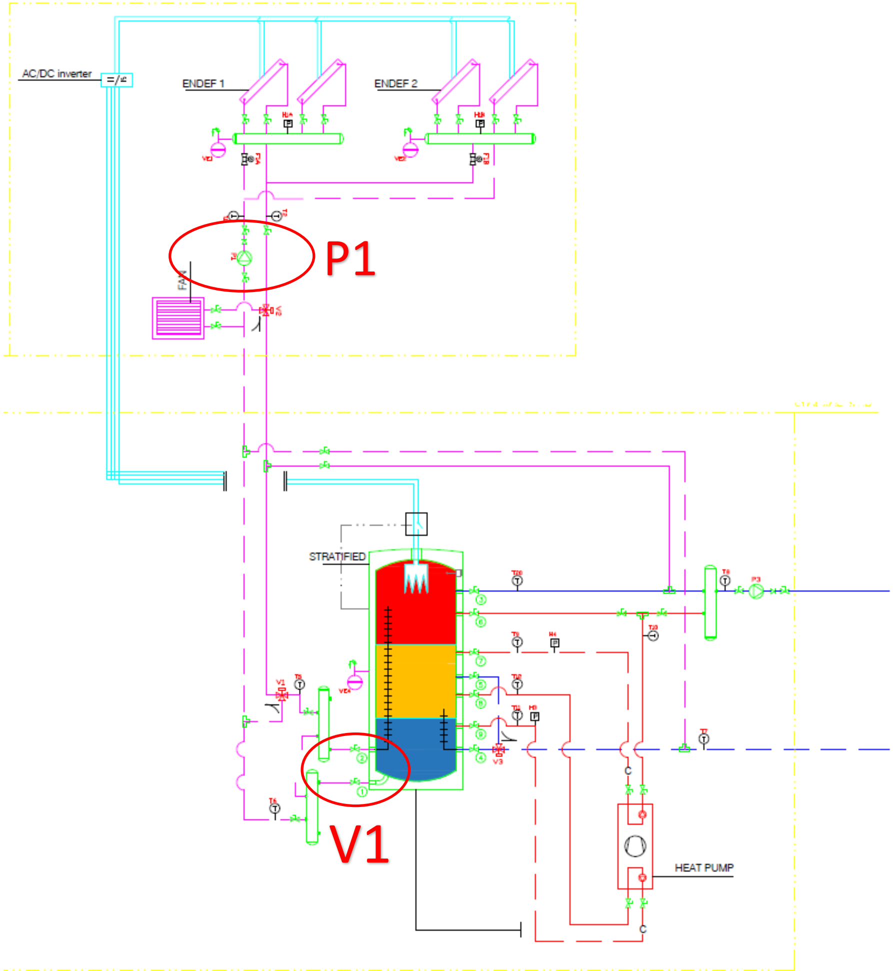


Figure 14. Diagram of the Solar field interconnected with the stratified tank, specifying the valve (V1) and the pump (P1)

Concerning the security strategy, there are mechanical devices like bleeders or isolated electrical connections were integrated in the system, in order to prevent electroshocking and typical problems related with air and water. The following figure illustrates where and how are these components installed on the panels side.

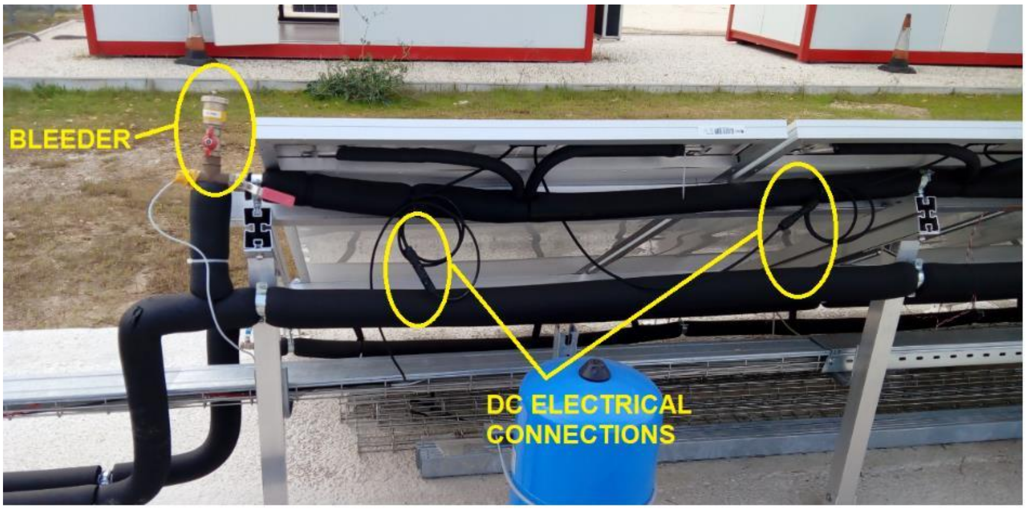


Figure 15. Bleeder and electrical connections in solar field.

Other security element completing the solar field installation is the dry cooler, which is installed to prevent overheating problems in the primary circuit due to an excess of heat produced when solar radiation is high. In this case, several actions are carried out:

1. The temperature is regulated by a PLC control system.
2. The circulation in the pump is produced, in order to avoid stagnation,
3. The deviation valves are controlled, closing the water loop
4. The connection with the storage tank is cut off, so all the heat is directly expelled to the air rejection system.

The next figure shows the installation of the dry cooler, with its correspondent temperature sensor.

Figure 16. Dry cooler (left) and temperature sensor for dry cooler system.

Finally, as a complement of this information, deliverable 4.6, section 8.1 includes the complete electrical diagrams for the solar field installation together with the stratified heat storage tank.

3.1.2 Data acquisition

The logical architecture of the monitoring and control network and the overall data acquisition procedure of the three solutions (HEAT-Low UP, COOL-Low UP and HP-Low UP) will be the same among the three concepts of the project with slightly differences, that are mainly reachable in deliverable 3.4, section 4. The LowUP Storage stores the data collected from each system in order to study its behaviour, to control its right performance, to allow its automatized operation and to analyse possible anomalies or alerts for a predictive maintenance of the systems. All data from the LowUP network will be generated and send to the repositories by using PLC or other monitoring devices. The repositories used for the three solutions are the following:

- High frequency repository: stores all raw data collected with the highest possible frequency by the network and PLCs. It is planned to store as much data as possible from any test. This database is occasionally removed, creating the csv files for each test, which in the next step will be moved to external storage systems, for further analysis.
- Historic repository: it has to store a minimal information of all systems involved in the demonstration of the three solutions of the LowUP project in order to have a complete and global picture of the performance of all systems working together during their daily usage. The frequency considered is 15 minutes.
- Other secondary data repositories: they run over embedded PCs connected to the PLCs, and include two databases with the same configuration of the main repositories in order to facilitate the data exchange. They play a bridge role, giving the capacity to export the data from those secondary data repositories to the main data repositories centralized in the Seville Demo site. Deliverable 3.4, section 5.4.1: provides a better about these systems.

In general, the main data provider of the data repositories will be the SCADA as a good way to integrate the majority of the systems. It will use a proprietary driver based on the ODBC and JDBC standards to connect with the data repositories and fill the repositories properly. In the case of the external demo sites, a software component will be developed to read, using the Modbus protocol, the data from the PLCs and to store them properly in the secondary data repositories. After that, another process will synchronize the main and secondary repositories.

- At the moment, the storage solutions will be based in a standard and free relational database. The Relational Data Base Management System (RDBMS) selected to that aim is MySQL, which offers enough capabilities to allow a fast response when data is inserted and consulted, and allows an organized and common structure.
- Finally, a REST API was developed, in order to allow the usage of the data stored in the different repositories (mainly the LowUP Manager described in Deliverable 3.4, section 5.4.1).

3.1.3 Monitoring and recording of the validation parameters

Done and described in deliverable 2.9, section 4. At this point, a first approximation about the control and monitoring method of the entire process is made, presenting the variables that should be measured for each of the technologies involved within the HEAT-LowUP and COOL-LowUP solutions. Although this content is also valid for the HP-Low UP solution, it is specially considered for the previous ones, because deliverable D2.9 presents the description of the Building Automation System and monitoring network devised for the building conditioning solutions developed under the LowUP project. The logical architecture of the monitoring and control network will be the same for all solutions, with slightly differences.

First, the overall architecture is described in general terms. The core part is focused on Seville's demo site, where most of the energy equipment will be installed. Each of the manufacturers of the individual systems (PV/T panels, storage tanks, radiant floor, back-up heat pump, chiller, and active chilled beams) will provide a proprietary Programmable Logic Controller (PLC) to interact with relevant sensors and actuators of their corresponding equipment and perform low-level control routines.

These proprietary PLCs will be selected by each manufacturer according to their normal engineering practice, so that LowUP solutions will impose minimal requirements at this level of the overall system and adaptability and replicability of the proposed solution is thus supported.

Moreover, data flows among SCADA, data repositories and different software modules that will be implementing the high-level control and surveillance capabilities of the overall solution, will be enabled and coordinated by a multi-task dedicated software manager: the 'LowUP Manager', which will communicate all software modules developed in the project and will orchestrate their communication as well as the communication with external software modules like the SCADA, any external database, and the embedded PC's of the external demo sites. it is better explained in deliverable D3.4, section 4.4.

From section 4.2, the different communication processes between the different elements of the control and monitoring system are described, namely:

- Communication among different WP2 demos sites (Seville and Badajoz):
- Communication among proprietary PLCs and Frontend PLC
- Communication among plant equipment (sensors, actuators, etc.) and proprietary PLCs
- Communication between Frontend PLC and SCADA software
- Internal communication between SCADA and LowUP software modules
- Internal communication between SCADA and Data repositories

Next, along section 4.3, SCADA´s operation is described and explained, as well as its Frontend PLC: ECLYPSE, its associated supervisor software: EC-Net, and its Graphic design and visualization interface: ENVYSION.

Finally, section 4.4 refers to the software modules developed by the technological partners (ACC, CAR, EUT-CTM) and specially used for the building automation. Concerning this, deliverable 2.19 only describes the software modules related specifically to the WP2 (HEAT and COOL LowUP). The description of the WP3 controls, the LowUP Storage and the LowUP Manager (HP LowUP) are available in deliverable D3.4.

These modules are the following:

- Weather forecasting: This module aims to define a forecasting for the weather variables that could affect the right comfort of a building.
- System models: It contains the simulation models of all systems involved in each WP2 solution. In order to know its expected behaviour and the results of operating the system with specific set points and inputs.
- Demand modelling: This module forecasts the daily demand using available data like weather forecasting, results of the systems models, etc.
- Residual energy sources model: This module aims to estimate the energy recovered from the external heat of wasted water in the external demo sites, in this WP2 case, from the student's residential building.
- Control & optimization: This model is the responsible to define the best set points for all the HVAC systems operating within the target buildings according to all the outputs of the previous modules, considering the energy flow and storage of the systems.

- Surveillance and predictive maintenance: This module aims to supervise the systems behaviour in order to detect any anomaly, any performance leak, etc and also to try to take care of all systems and their components in a predictive way, when possible, to minimize the maintenance costs.

3.1.4 KPI monitoring

Monitoring variables should respond to the needs from control, surveillance and evaluation objectives. Therefore, a first definition of the technical Key Performance Indicators (KPIs) was done considering the expected impacts of the project. In deliverable 2.9, section 5.1, the general KPIs for the HEAT - LowUP solution are defined:

Table 2: Expected impacts for LowUP building solutions (according to the DoA)

HEAT – Low UP expected impact (according to the DoA):
▪ 30% savings of expected GHG emissions (compared with a conventional system). ▪ 8% of total HVAC energy demand covered by residual heat ▪ 16% of total HVAC energy demand covered by renewable energy ▪ 18% of expected primary energy saving (compared with a conventional system).

Table 3: KPIs defined for the overall HEAT-Low UP solution

	KPI			Parameters for the calculation			
System	Symbol	Unit	Description (type)	Symbol	Unit	Previous KPI?	Description and/or comments
HEAT-LowUP system	GHG_s	$kgCO_2eq$	GHG emissions saving compared with a conventional system (G)	η_{CS}	-		Efficiency of the conventional system
				PEF_E	-		Primary energy factor of electricity
				PEF_{CS}	-		Primary energy factor of the final energy consumed by the conventional system
				GHG_{CS}	$kgCO_2eq$		GHG emission factor for primary energy consumed by the conventional system
	PES	kWh	Primary Energy Savings (E)	GHG_E	$kgCO_2eq$		GHG emission factor for electricity
				PEF_E	-		Primary energy factor of electricity
				PEF_{CS}	-		Primary energy factor of the final energy consumed by the conventional system
	P_{aux}	kW	Electric power consumed by auxiliary equip. (E)	P_{aux}	kW		
	E_{aux}	kWh	Energy consumed by auxiliary equipment (E)	E_{aux}	kWh		Indirect calculation from P_{aux}
	f_{RES}	-	Fraction of heat demand	$Q_{ECO,R}$	kWh	Yes	Thermal energy recovered by the ECOWEC system

			covered by residual energy sources (E)	$Q_{fluid,RF}$	kWh	Yes	Thermal energy delivered by the fluid to the radiant floor (i.e. total heat demand)
	f_S	-	Fraction of heat demand covered by solar energy (E)	Q_{PVT}	kWh	Yes	Thermal energy recovered by the PVT system
				$Q_{fluid,RF}$	kWh	Yes	Thermal energy delivered by the fluid to the radiant floor (i.e. total heat demand)
	f_{HP}	-	Fraction of heat demand covered by the HP (renewable or not depending on sCOP) (E)	Q_{HP}	kWh	Yes	Thermal energy delivered by the HP
				$Q_{fluid,RF}$	kWh	Yes	Thermal energy delivered by the fluid to the radiant floor (i.e. total heat demand)
	f_{REN}	-	Fraction of heat demand covered by renewable energy sources (E)	sCOP	-	Yes	Seasonal COP of the HP (to consider it as renewable energy source or not)
				f_S		Yes	Fraction of $Q_{fluid,RF}$ covered by solar
				f_{HP}		Yes	Fraction of $Q_{fluid,RF}$ covered by renewables
	PPDh	%-hour	Cumulated global discomfort indicator (C)	T_{op}***	C		Operative temperature
				PPD_{lim}	%		Maximum limit of PPD according to comfort criteria (e.g. from ISO7730)

Next, the list of the identified KPIs for the Hybrid solar panel is specified in Table 4 (also available in the same deliverable):

Table 4: KPIs detailed for the PVT-PCM solar panels

	KPI			Parameters for the calculation			
System	Symbol	Unit	Description (type)	Symbol	Unit	Previous KPI?	Description and/or comments
PVT-PCM solar panels	P_{solar}	kW	Total solar irradiation on solar panels (E)	G_0	W/m²		Solar irradiance on PV surface
				A_{col}	m²		Area of solar panels surface
	$P_{elec,PVT}$	kW	Electric power produced by the PVT system (E)	$P_{elec,PVT}$	kW		
	$P_{therm,PVT}$	kW	Thermal power recovered by the PVT system (E)	$m_{w,PVT}$	kg/s		Solar panels mass flow rate
				$T_{win,PVT}$	C		Solar panels inlet temperature
				$T_{wout,PVT}$	C		Solar panels outlet temperature
	E_{solar}	kWh	Availability of solar resource (E)	E_{solar}	kWh		Indirect calculation from P_{solar}
	E_{PVT}	kWh	Electric energy produced by the PVT panels (E)	E_{PVT}	kWh		Indirect calculation from $P_{elec,PVT}$

	Q_{PVT}	kWh	Thermal energy recovered by the PVT system (E)	Q_{PVT}	kWh		Direct measurement from energy meter
	$\eta_{elec,PVT}$	-	Instantaneous electric performance of the PVT system (E)	$P_{elec,PVT}$	kW	Yes	Electric power produced by the PVT system
				P_{solar}	kW	Yes	Total solar irradiation on solar panels
	$\eta_{therm,PVT}$	-	Instantaneous thermal performance of the PVT system (E)	$P_{therm,PVT}$	kW	Yes	Thermal power recovered by the PVT system
				P_{solar}	kW	Yes	Total solar irradiation on solar panels
	SEP_{PVT}	-	Seasonal Electric Performance of the PVT system (E)	E_{PVT}	kWh	Yes	Electric energy produced by the PVT panels
				E_{solar}	kWh	Yes	Availability of solar resource
	STP_{PVT}	-	Seasonal Thermal Performance of the PVT system (E)	Q_{PVT}	kWh	Yes	Thermal power recovered by the PVT system
				E_{solar}	kWh	Yes	Availability of solar resource

3.1.5 Results validation of the prototype system installed in a real emplacement

- Heat recovery kit to PV panels:

  A heat recovery kit has been applied to the Demo site of Seville, configuring a solar field of 40 photovoltaic-thermal (PVT) panels. To better determine the effect of the PCM, solar field has been distributed in two parallel lines: one with 20 plain PVT panels (line w/o PCM) and second with 20 PVT panels with a layer of phase-change material PCM inserted (line w/ PCM).

  Solar field has been running during the summer months of Spain, that is, from May to the present day, although has been designed to operate during winter months to provide heating to the office building. Warm months have been used to test the solar field under different external conditions such us thermal loads, environmental aspects and temperature control. It should be remarked that lower energy generation is expected in winter due to the decrease on the solar radiation, but higher efficiencies when the system works in a lower temperature and under a constant heating load.

  Following conclusions may be extracted from the testing months.

- Ratio thermal/electrical production in PVT panels of 2:1:

  As an average during summer months, unglazed PVT panels were able to produce around the double thermal energy versus the electrical energy on the same module, reaching to daily energy productions of 48 kWht and 18 kWhe for the line without PCM and 55 kWht and 24 kWhe for the line with PCM. Thermal and electrical efficiencies of PV/T solar panels present an average values of 25% - 9%, and 32% - 13% for the line without and with PCM. These values may be enlarged or reduced depending on the working mode of the installation (see Figure 17 for the detailed energy distribution in August). When there is no electrical generation (e.g. last days of August), the thermal efficiency is increased in a 10-15%.

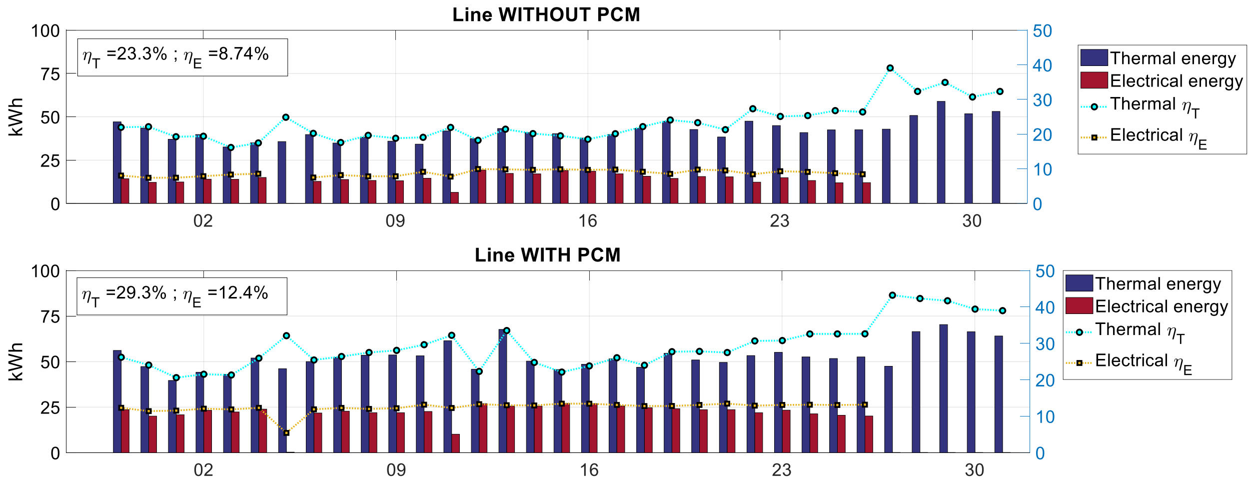


Figure 17: Thermal and electrical performance (energy and daily efficiencies) for August.

- Energy performance strongly dependent on the working mode

  The position of the intermediate valves in the solar circuit (between the field, the storage tank and the thermal loads) determines if the solar field operates in a close loop, throws into the storage tank or provides heat to a external device. This operation mode directly affects to the energy performance of solar panels. As a general rule, higher thermal efficiencies are found when the solar field works with a high thermal load or when the storage tank is cold at the beginning of the day. On the contrary, lower thermal values are shown when the system works in a close loop or the tank is too warm. Then, the solar fields is not able to evacuate the heat generated and the temperature increase penalizes the thermal and electrical performance.

- No reduction on operating temperature due to the PCM addition

  Contrary to expectations, the use of PCM does not lead to a reduction of the operating temperature, but fluid temperatures keep quite similar in both lines. It may be explained because the PCM used in this case has a melting point (48°C) much higher than other studies (between 20-30°C), and then the PVT solar field is not able to work for a long time over this temperature to provoked a reduction in the operating temperature.

- Significant improvements in thermal and electrical performance resulting from the PCM addition

  Despite not finding significant differences in working temperature, the addition of PCM provokes meaningful improvements in the energy performance of the solar circuit, ranged between 25-35% in the PV performance and 20-60 % in the thermal performance, depending on the case. The PCM insertion seems to have direct influence not only in the energy generated at the end of the day, but also the thermal and electrical efficiencies exhibited during the sun hours.

  This improvement suggests that the inclusion of PCM favours the heat transmission from the backside of the PV laminate to the heat absorber and the PCM enclosure, making the PV cell working in a lower temperature and transferring more heat to the fluid. It would explain the increase on the instantaneous thermal and electrical efficiencies.

- The great storage volume favours the PV/T panels energy efficiency

  The great volume of the storage tank, as well as the stratification capacity, allow the solar circuit to operate with acceptable efficiencies even in those days without heating load. Efficiency values are comparable to those obtained with heat evacuation and in case of high temperature, this storage capacity is endorsed by the storage capability of the PCM. This fact may be very beneficial to guarantee the energy generation during weekends, when the office does not consume thermal energy.

3.1.6 Next steps to reach next TRL

The heat recovery kit has been applied to PV panels giving rise to two models of PV/T panels: with and without PCM inserted. Both types should be differentiated to consider the TRL grade.

- Heat recovery kit without PCM

The unglazed PV/T panel developed during the project has become a commercial reality in the frame of the project duration, so it has reached to TRL9. From the initial design, several modifications on the initial geometry have been applied to improve the thermal performance and facilitate the installation process. Nowadays, this product has already been installed in several locations and is currently available to general customers in EndeF´s product portfolio.

- Heat recovery kit with PCM

This product remains in a lower TRL due to the strong innovation character associated to the use of PCM inside the panel. Thanks to the project, the prototype has been :

- manufactured in full scale (TRL4),
- individually tested in EndeF facilities with natural irradiance (TRL5),
- tested in a 20-panel installation in a close loop in Seville Demo (TRL6)
- and currently, tested in an operation environment (TRL7)

However, during the testing period of the installation, several operating problems of this type of panel have been identified that make it difficult to move to higher TRLs. Among these problems are the presence of leaks in some of the PV/T-PCM panels, which reveals a defect in the enclosure of any of the internal packages, and the metal corrosion derived from the PCM drip.

Moreover, despite the demonstrated energy benefits of the PCM in the final performance of the installation, the economical viability of this solution still remains unclear. The cost of PCM in the format required for the panel application (flat PCM pouches) and for small orders (below 50 panels) is really high comparing the rest of the solar components. This economical aspects hinders the possibility of increasing TRL.

Next steps to improve the TRL could be:

- Further investigations on PCM enclosures to avoid leaking problems without penalizing the thermal conductivity of the resulting system.
- A reduction in the PCM cost that improves the PV/T-PCM panel profitability.

3.2 Component 2: Stratified Tank

The stratified tank manages the energy provided by the low-temperature heat sources of the system, collecting heat from the following sources:

1. Direct conversion of electric energy PV production
2. Recovered heat from domestic areas

The stratified tank device has to cover the heating demand of the radiant floor installation of the office building.

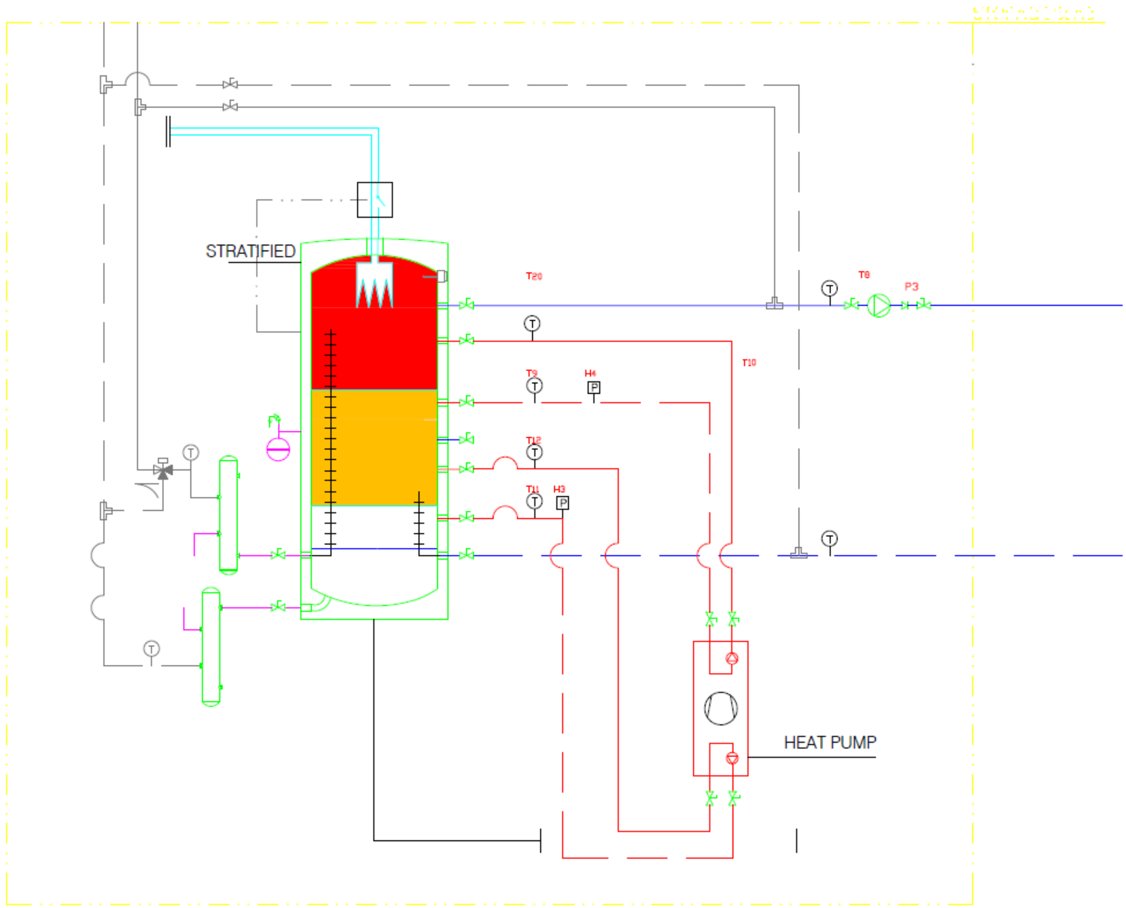


Figure 18. Stratified Tank System

The lower part of the tank is fed from the solar field and the heat recovery emulator; the thermal energy flows from the bottom of the tank along the stratification column to its respective temperature layer (generally at the top of the tank, which is connected to the radiant flow, in order to exploit the higher stored temperature.

The lower part of the tank is the cold sink connected to the w-t-w heat pump, while its hot sink is the upper part. Moreover, there are controlled electric resistances installed serving as a backup system.

The characteristics of the final device are here detailed (deliverable 4.6):

- Size: DN 1600mm x H 3550mm
- Working pressure 3 bar
- Stratified loading port for solar thermal energy of 1 "IG

- Maximum flow 4,000l / h
- Maximum temperature 90°C
- Stratified cargo port for grey water recovery of 1 "IG
  - Maximum flow 2,000l / h
  - Maximum temperature 90°C
- Stratified loading port for the 1 "IG heat pump
  - Maximum flow 2,000l / h
  - Maximum temperature 90°C
- 1 "IG laminated radiant floor return port
  - Maximum flow 7.000l / h
  - Maximum temperature 90°C
- Laminated resistance of 3 * 2,5kW
- 14 sensor sockets
- Top purge of 1 "IG
- Lower 1 "1 / 2IG drain
- Insulation 120mm for heat - Hub 6,500 litres

Figure 19. Stratified tank installed the demo site in Seville

The main specific features and operation aspects considered for this system are here explained (deliverable 2.7 and 2.11):

- Stratified tank:
  - The backup HP is connected through fixed ports
  - The radiant floor heating system return is connected to an internal stratification column, while the supply comes out from a fixed port in the upper zone of the tank

- The PV/T and waste heat sources are mixed upstream the tank and share the connection through one unique internal stratification column; the return of both systems comes out from the bottom part of the tank

3.2.1 Sensor selection and physical emplacement

A general explanation about sensors, including their description, operation, and role in both HEAT-LowUP and COOL LowUP solutions can be found in section 3.1.1 of this document, which is, in turn, extracted from deliverable 2.9, section 5.3, deliverable 2.9, Annex 2 and deliverable 4.6, section 2.3.

Concerning the stratified tank, in order to test the efficiency of the heat stratification and monitor its behaviour, the tank is equipped with a specific temperature monitoring system based on the vertical distribution of temperature probes in contact with the water. A total of 12 temperature sensors are installed, with their correspondent immersion cases aligned in the vertical of the tank (see Figure 18, Figure 20 and Figure 21) which are of course included in the manufacturing process of the equipment. For more detail, see deliverable 2.7, section 4.6 and deliverable 4.6 section 2.1.2.

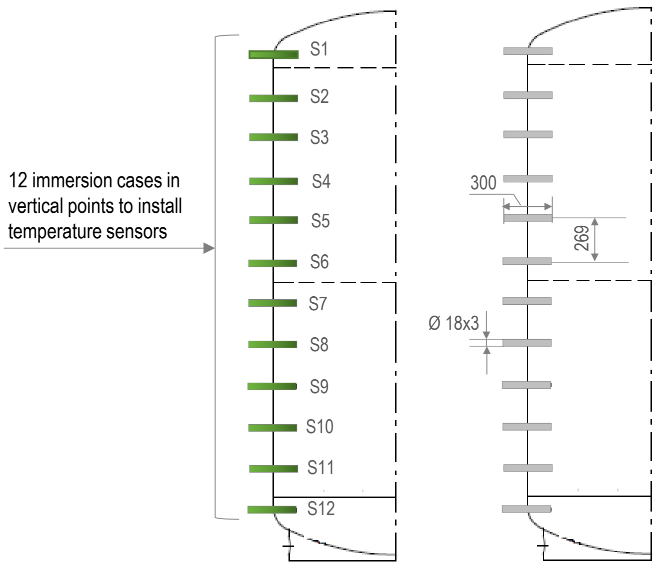


Figure 20. Sensors distribution along the storage tank

Figure 21. Temperature sensor in the storage tank.

In addition, the tank includes a monitoring system in order to observe and control tank temperatures and to establish communication with the general control system of the LowUp Pilot Plant in Sevilla. In relation to this requirement, the tank has to be provided with a PLC, which allows receiving the measurements of the temperature sensors (not included) and can send and receive data from the general control system with a Modbus RTU (RS485) or KNX protocol.

Finally, as a complement of this information, deliverable 4.6, section 8.1 includes the complete electrical diagrams for the solar field installation together with the stratified heat storage tank.

3.2.2 Data acquisition

The content here is the same as in section 3.1.2 of this document, applicable for all HEAT Low-UP, COOL Low-UP and HP Low-UP solutions.

3.2.3 Monitoring and recording of the validation parameters

The content here is the same as in section 3.1.3 of this document, applicable for both HEAT Low-UP and COOL Low-UP solutions.

3.2.4 KPI monitoring

The list of the identified KPIs for the Stratified thermal storage tank is shown in Table 5 (available in deliverable 2.9, section 5.1):

Table 5: KPIs detailed for the Stratified Thermal Storage Tank

	KPI			Parameters for the calculation			
System	Symbol	Unit	Description (type)	Symbol	Unit	Previous KPI?	Description and/or comments
Stratified thermal storage tank	ΔT_{tank}	C	Thermal stratification: Temperature difference between the top and bottom of the tank**	$T_{tank,t}$	C		Top tank temperature
				$T_{tank,b}$	C		Bottom tank temperature

3.2.5 Results validation of the prototype system installed in a real emplacement

In case of high temperature, this storage capacity is endorsed by the storage capability of the PCM. This fact may be very beneficial to guarantee the energy generation during weekends, when the office does not consume thermal energy. Attending to the stratification capacity, it has found to be greater when the starting temperature of the stored water is low. This fact is explained by two reasons:

- First: the valve between the solar field and the storage tank is opened when the outlet temperature of the solar panels exceeds a certain value, commonly set by the user between 35-45°C. If the stored temperate is low with respect to the solar field, the gradient between the stored water and the liquid coming from the solar panels is really high, which favours the stratification.
- Second: when the solar field operates under the required temperature (also set by the user) the pump reduces the fluid flow circulating through the panels to reach maximum temperature in the outlet. Thus, the amount of hot water entering the storage tank from the solar field is reduced, favouring again the stratification.

Two examples of stratification are shown in Figure 22 and Figure 23Figure 25, corresponding to days with cold and hot tank at the beginning of the day.

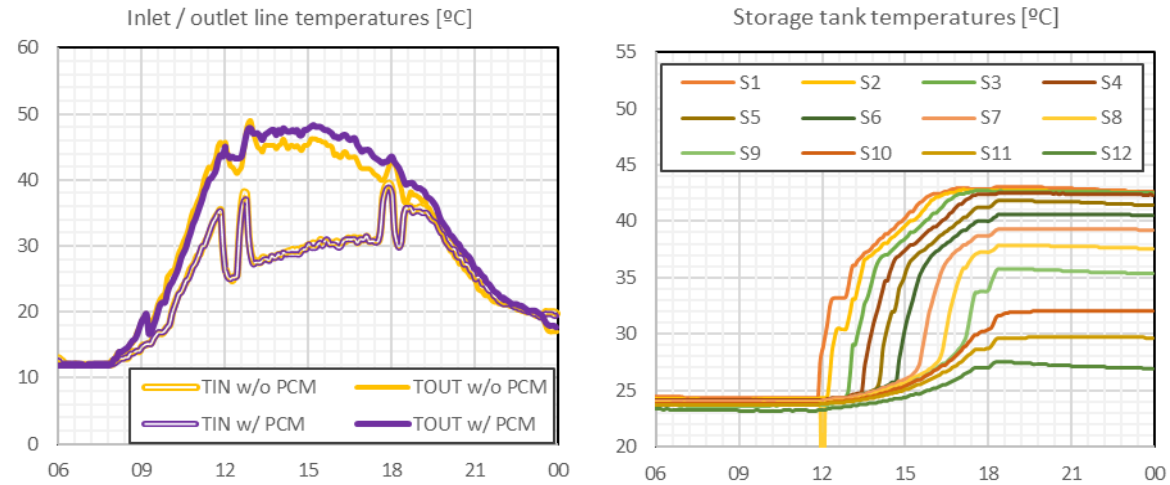


Figure 22: Temperature profile in the inlet/outlet lines (left) and storage stratification (right), cold tank.

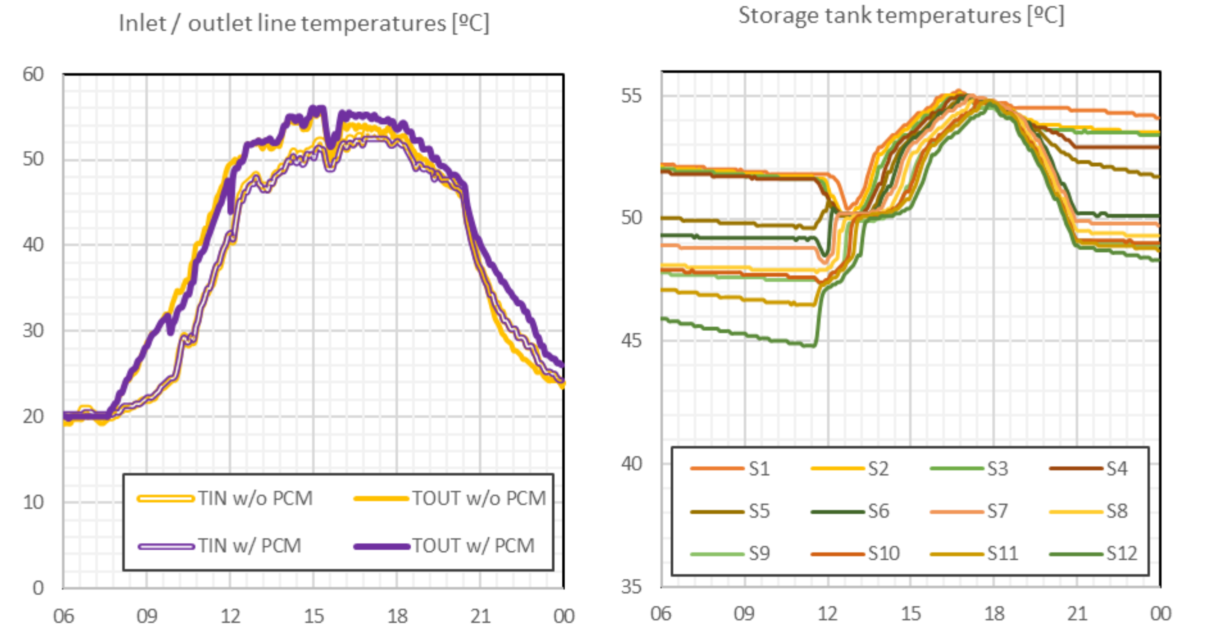


Figure 23: Temperature profile in the inlet/outlet lines (left) and storage stratification (right), hot tank.

Next image show behaviour of pumps speed regulating in function of outlet temperature from solar field and effect over stratification of tank.

Color:	Variable:	Unit:	Operation:
blue	spump speed	%	pump with variable speed for setpoint temperature
red	Tout solar	°C	
others	S1-S12	°C	

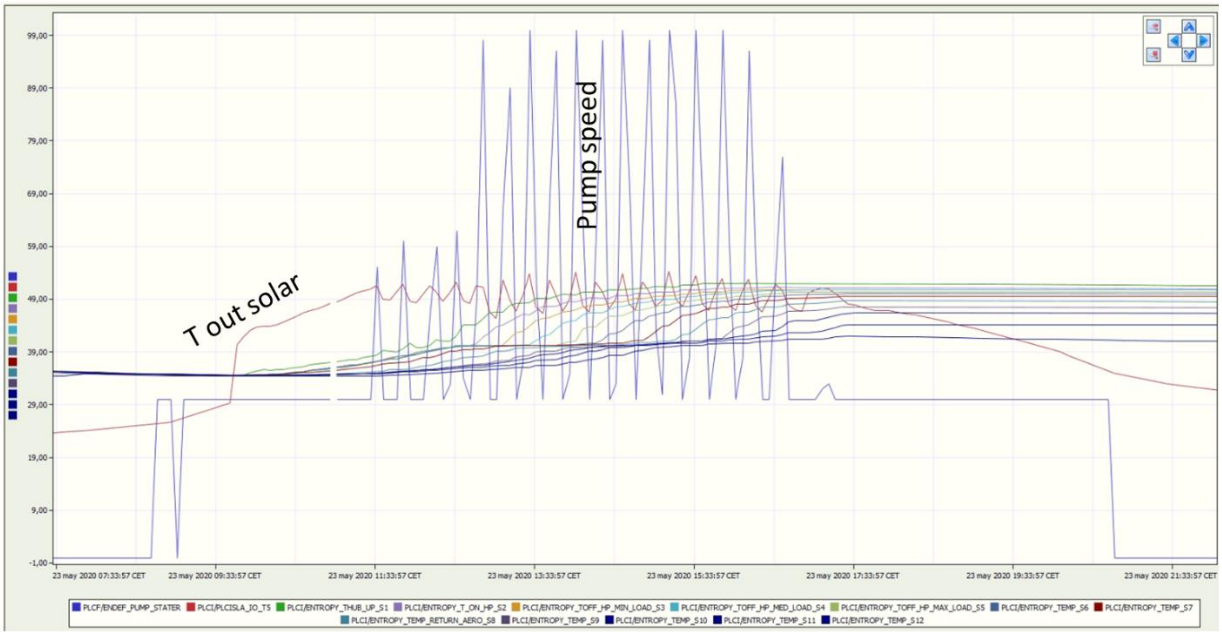


Figure 24: Temperature distribution over tank during day with variable temperatures

Regulation of temperature allows achieving desired temperature on top of stratification tank; when temperature from solar field starts lowering and speeds sets at 30%, the 3ways valve (that connect solar with tank) recirculates flow only over solar field for avoiding negative charge of tank.

Although the energy improvement derived from the use of PCM is undeniable, some small leaks have been observed in the lower part of several PV/T panels. Our belief is that due to the PCM nature (inorganic, a salt hydrate) it solidifies creating sharp spikes, that taking into account the thin space of the PCM layer and the pressure applied from the rest of the solar panel components, may have pierced the aluminium envelope.

Although the total amount of PCM leak is not significant, this constitutes a serious problem, since the it is a very corrosive and conductive material that may damage the material on which it falls or provoke a short circuit in undesirable points.

3.3 Component 3: Radiant Floor Heating System (RDZ)

The main goal of the LowUp underfloor heating system is to create a new system that can be fed not only with alternative energies, but even with waste water, using its residual thermal energy as provider. For this purpose it's been designed an high-efficiency floor radiant system which is able to work with particularly low water supply temperatures (around 30-35°C). RDZ is in charge of this development, which is more extensively reported in deliverable D2.3.

To carry out this kind of system, several requirements have to be fulfilled:

- Very high efficiency
- High uniform temperature
- 60 W/m^2 of heat supply for a 20°C room comfort temperature.
- Design flow rate of 10 $l/h{\cdot}m^2$.
- Low inertia

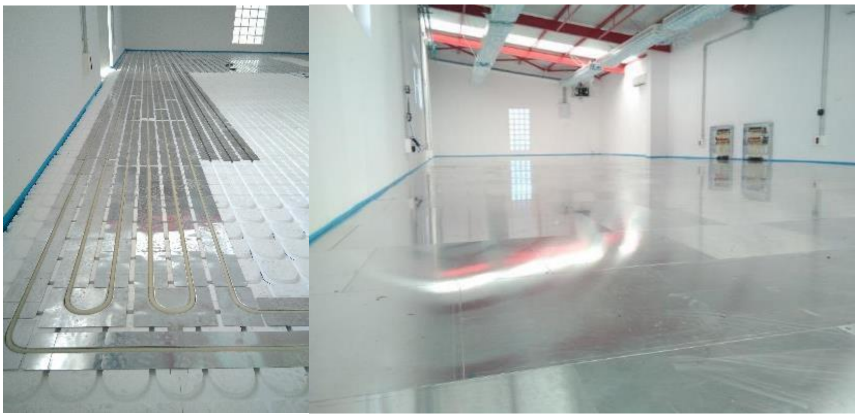


Figure 25. Pipes inside radiant floor (left) and last layer (metallic) of radiant floor (right)

The radiant floor installation is based on dry installation concept, in which the tubes are not embedded in the concrete, but are placed over an insulation layer with specific shape for installation of curves.

The system is directly fed by the stratified heat storage tank, so with variable temperature depending on the availability of the sink during the different hours of the day along the season.

This unit shows a 72,90 W/m² power deployment and 20,70 L/h·m².

The selected material was copper pipe, which is able to achieve completely the goal of 60 W/m² of thermal power transmitted.

The characteristics of the final device are here detailed (deliverable 4.6):

Table 6. Design characteristics of the radiant floor system

TM theoretical [°C]	ΔT theoretical [°C]									
38,4	5,0									
Collector	att.	TM [°C]	Power [W]			Caudal [l/h]	PDC [mmH2O]	Fabb. pipe [m]	H2O tub [l]	Sup. covered [m²]
			High	Low	Total					
Coll 1	8	31,0	3465	778	4243	1200	3927	484	38	
Coll 2	8	31,0	3445	770	4215	1200	3904	481	38	
Totals	16		6910	1547	8457	2400	3927	965	76	116

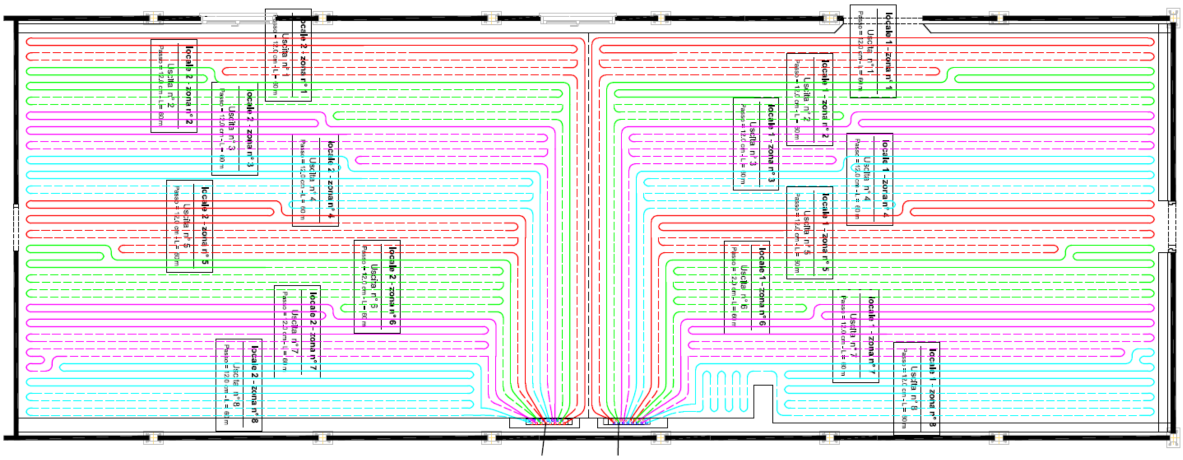


Figure 26. Schema of water pipes of the radiant floor system

3.3.1 Sensor selection and physical emplacement

A general explanation about sensors, including their description, operation, and role in both HEAT-LowUP and COOL LowUP solutions can be found in section 3.1.1 of this document, which is, in turn, extracted from deliverable 2.9, section 5.3, deliverable 2.9, Annex 2 and deliverable 4.6, section 2.3.

Focusing on the actual radiant floor heating installation, deliverable 4.6 section 2.1.2 specifies several features and describes how this system works. It is based on a dry installation concept, in which the tubes are not embedded inside the concrete, but placed over an insulation layer with specific shape adapted to the curves described by the tube.

The system is directly fed by the stratification tank, with variable temperature depending on the availability of the sink during the different hours of the day along the season.

Components of radiant floor are listed below:

- Collectors.
- Thermal energy meters.
- Regulation accessories.
- Water circuit connection accessories.

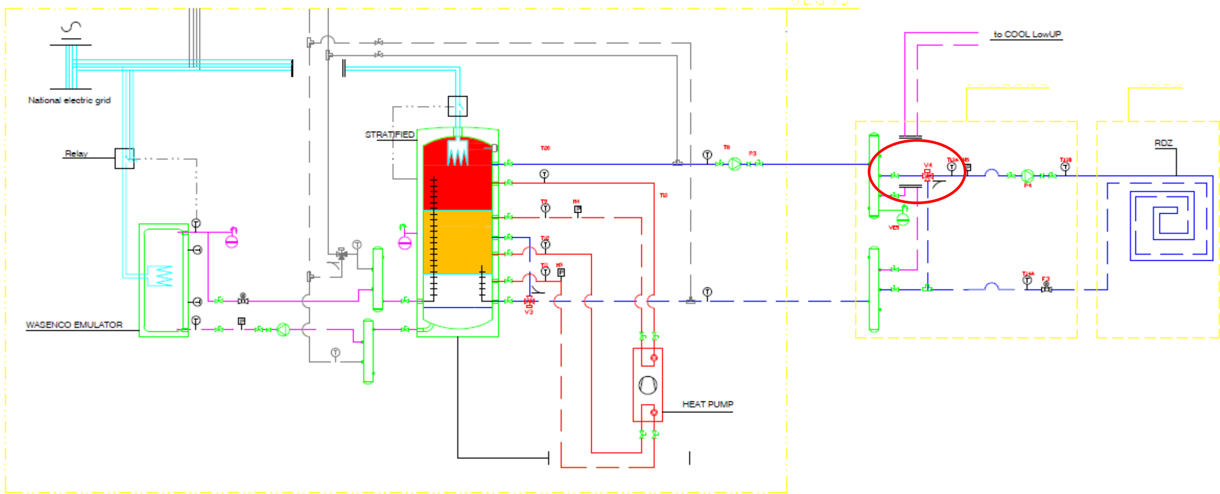


Figure 27. Diagram showing the interaction between radiant floors and the rest of the HEAT LowUP installation. Thermostat appears, acting upon a 3-way valve

Thermostat devices are used to regulate indoor temperature through the ON/OFF actuation comparing the indoor temperature measure with a predefined value. The control strategy actuates on the energy production unit and also on the pumps and valves of the secondary circuit. The regulation fixes a constant established temperature for the most unfavourable winter conditions, un such a way that the flow temperature is set regardless of the outdoor conditions. All these concepts are displayed in Figure 27.

Table 7. Control strategy of the radiant floor in combination with other systems

Regulation	Radiant system	Air conditioning	External conditions adaptation	Occupation adaptation	Regulation efficiency level
Fixed point	YES	NO	NO	NO	1
Climatic	YES	NO	YES	NO	2
Climatic (advanced)	YES	YES	YES	YES	3

Finally, as a complement of this information, deliverable 4.6, section 8.2 includes the complete control diagram for the radiant floor installation.

3.3.2 Data acquisition

The content here is the same as in section 3.1.2 of this document, applicable for all HEAT Low-UP, COOL Low-UP and HP Low-UP solutions.

3.3.3 Monitoring and recording of the validation parameters

The content here is the same as in section 3.1.3 of this document, applicable for both HEAT Low-UP and COOL Low-UP solutions.

3.3.4 KPI monitoring

The list of the identified KPIs for the radiant floor system is shown in Table 8**¡Error! No se encuentra el origen de la referencia.** (available in deliverable 2.9, section 5.1):

Table 8: KPIs detailed for the Radiant Floor System

	KPI			Parameters for the calculation			
System	Symbol	Unit	Description (type)	Symbol	Unit	Previous KPI?	Description and/or comments
Low-temperature radiant floor system	$P_{fluid,RF}$	kW	Thermal power delivered by the fluid to the radiant floor (E)	$m_{w,RF}$	kg/s		Water mass flow rate at the radiant floor main circuit
				$T_{win,RF}$	C		Radiant floor water inlet temperature
				$T_{wout,RF}$	C		Radiant floor water outlet temperature
	$P_{surf,RF}$	kW	Thermal power delivered by the radiant floor to the indoor environment (E)	T_{op}***	C		Operative temperature
				T_{surf}	C		Radiant floor mean surface temperature
				h_{tot}	$W/(m^2C)$		Total heat transfer coefficient (e.g. correlations from EN15377)
	$Q_{fluid,RF}$	kWh	Thermal energy delivered by the fluid to the radiant floor (E)	$Q_{fluid,RF}$			Indirect calculation from $P_{fluid,RF}$
	$Q_{surf,RF}$	kWh	Thermal energy delivered by the radiant floor to the indoor environment (E)	$Q_{surf,RF}$			Indirect calculation from $P_{surf,RF}$

3.3.5 Results validation of the prototype system installed in a real emplacement

The radiant floor has been tested even during cooling period through utilization of 2 air conditioning splits used for generating fictitious heating loads; splits were sets to maintain indoor temperature at 18°C and tests are executed during night. During heating season, all tests were repeated to confirm results previously achieved; tests have been executed according to following table:

Table 9: Operation points

Parameter	Unit	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
Water flow rate	l/h)	2000 (~1550)				2600 (~2200-Nominal)			
Inlet water temperature	ºC	25	30	35	40	25	30	35	40
Outlet water temperature	ºC	[Monitored]							
Surface temperature	ºC	[Monitored]							
Room temperature	ºC	20ºC [monitored. Ideally constant]							

Ambient temperature	ºC	[Monitored]

Indoor temperature achieved is 20°C by water at 30°C. In orange box is presented the moment when test finishes and splits are switched off, while the floor is still operating; as consequences indoor temperature rises without control.

Color:	Variable:	Unit:	Operation:
blue	Temp IN	°C	pump with constant speed and 3ways valve regulating for setpoint temperature
green	Temp OUT	°C	
light blue	Room temp	°C	
red	water flow	lt/h	
violet	out temp	°C	

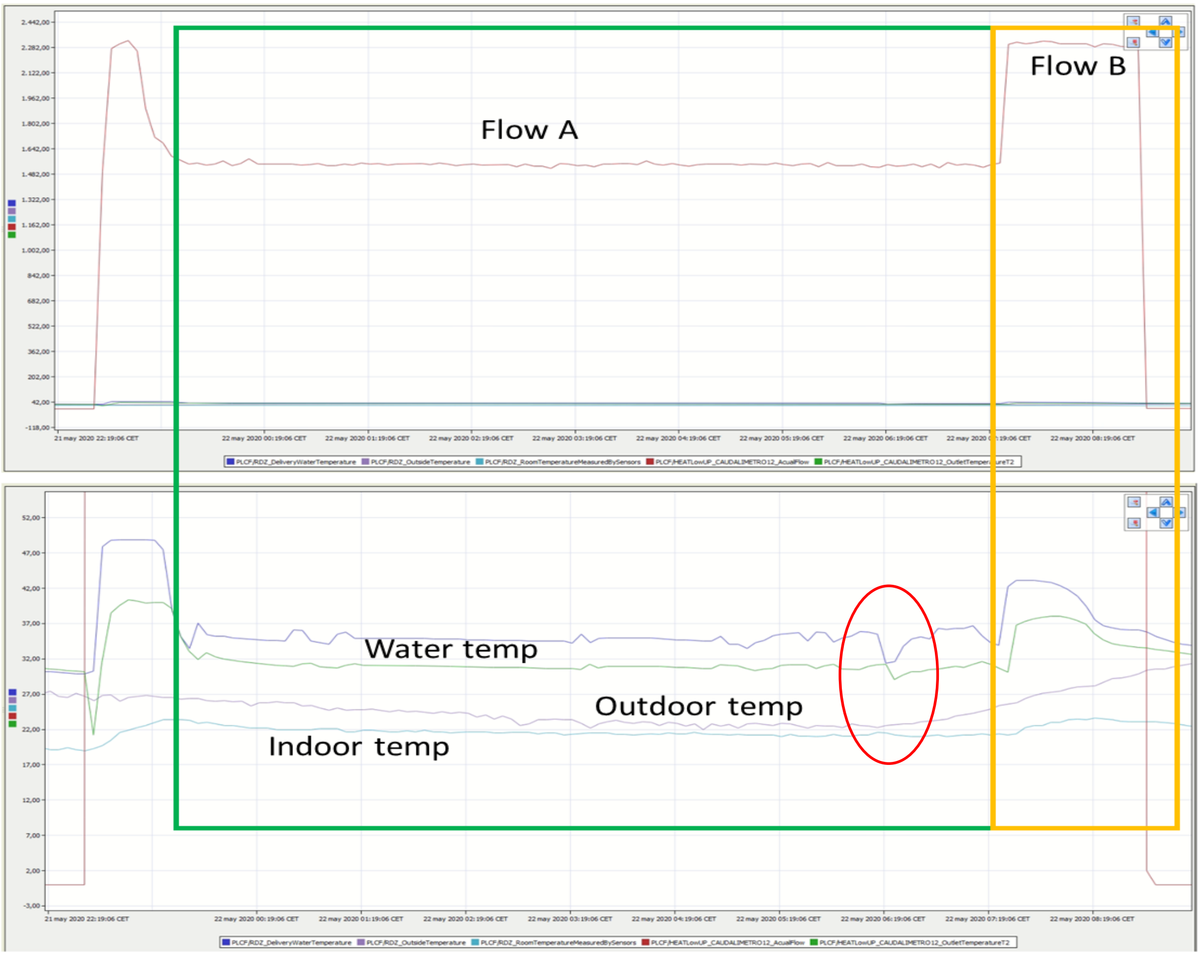


Figure 28: Temperature distribution for indoor office with radiant floor at 35ºC and 1.550 - 2.600 lt/h

Previous figure shows how indoor temperature achieved is 22°C by water at 35°C. It can be noticed how sudden increment of flow determines increment of water temperatures because of delay in regulation of 3ways valve; the valve receive heat from stratified tank at higher temperature than radiant floor supply temperature.

Next figure shows how 3ways valves tends to compensate fluctuation of temperature given by splits, which are affected by outside temperature and cannot produce cool in stable way. Temperature are fluctuating but in a range of 2K.

In red circle is showed reduction of inlet water temperature because of regulation of 3ways valve due to “peak” of indoor temperature.

Color:	Variable:	Unit:	Operation:
blue	Temp IN	°C	pump with constant speed and 3ways valve regulating for setpoint temperature
green	Temp OUT	°C	
light blue	Room temp	°C	
violet	out temp	°C	

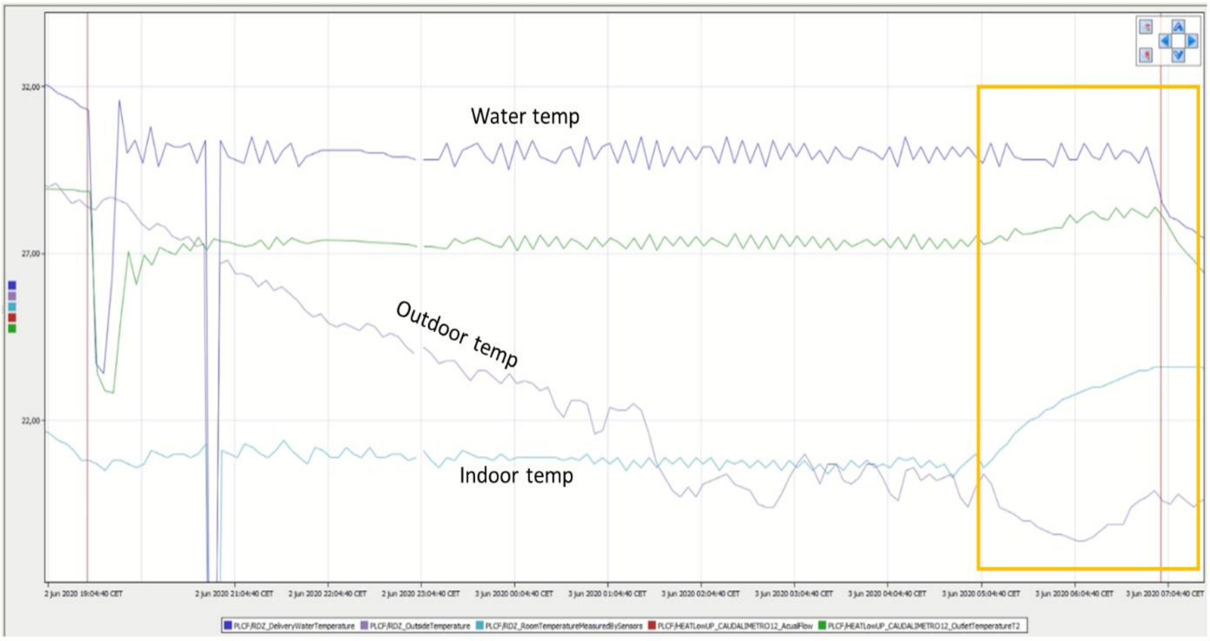


Figure 29: Temperature regulation of floating load by radiant floor at 30ºC

Next figure presents combination of stratified tank with radiant floor; water from higher tank layers is moved to radiant floor where is regulated by 3ways valve for room temperature control.

Color:	Variable:	Unit:	Operation:
blue	Temp IN	°C	pump with constant speed and 3ways valve regulating for setpoint temperature
green	Temp OUT	°C	
light blue	Room temp	°C	
violet	out temp	°C	

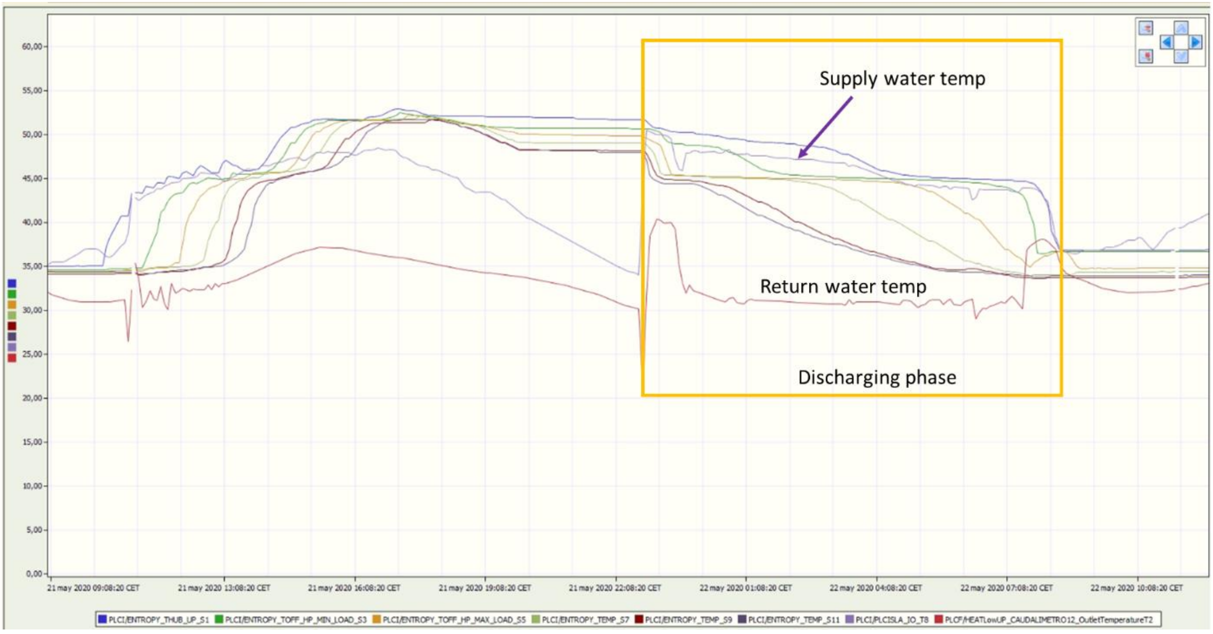


Figure 30: Radiant floor supplied by stratified tank

Next image presents energy delivered as function of supply temperature:

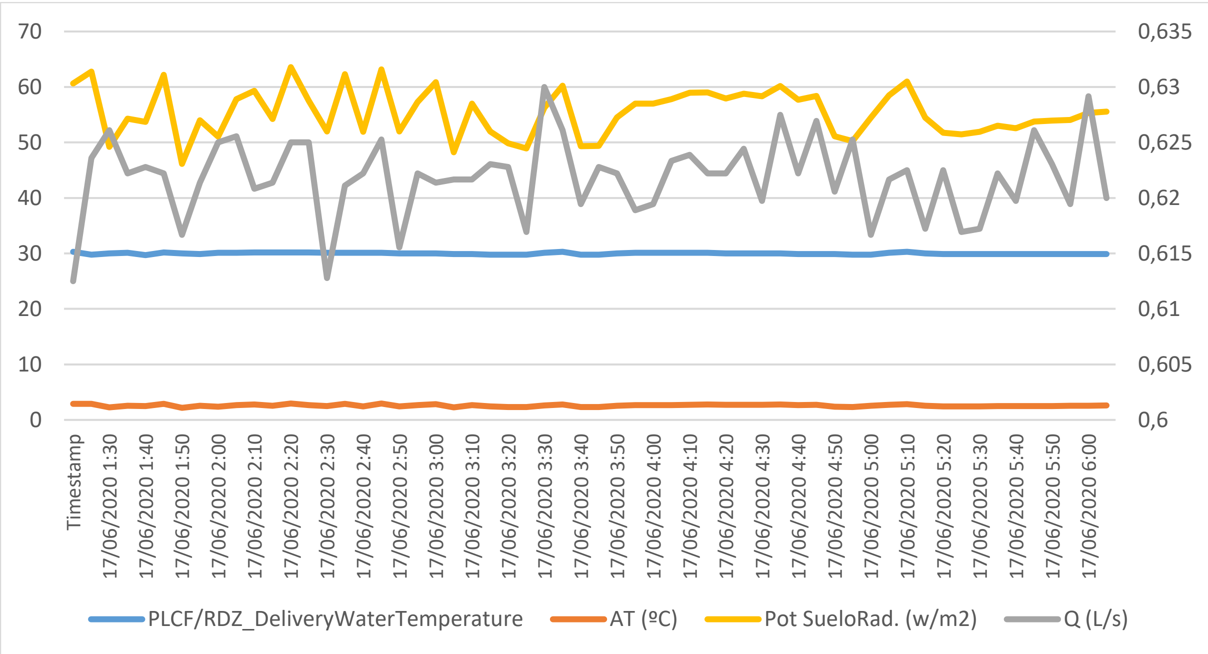


Figure 31: Radiant floor delivered power at 30ºC

It is possible appreciate how radiant floor is close to 60 W/m^2 and in different moments overcome this target value; here below resumed are shown average calculated results from monitoring:

Table 10 – Radiant floor performance

PLCF/RDZ Delivery Water Temperature	PLCF/RDZ Room Temperature Measured By Sensors	AT Imp-Amb (°C)	AT (°C)	Q (L/s)	P=4·Q·AT (kW)	Pot Rad. Floor (w/m2)
30,00	21,39	8,61	2,59	0,62	6,43	55,45
34,98	22,33	12,64	2,95	0,63	7,43	63,87

Conclusion of the Test

The systems is working properly and when the tank temperature is above the 30°C the system (see the test report in Stuttgart) can achieve at 60 W/m_2 . About the TEST NUMBER 1 there are some point to check like the position of external temperature sensor (we suggest to fix it to a north wall in brick), and the state of the control unit during some period (ON position).

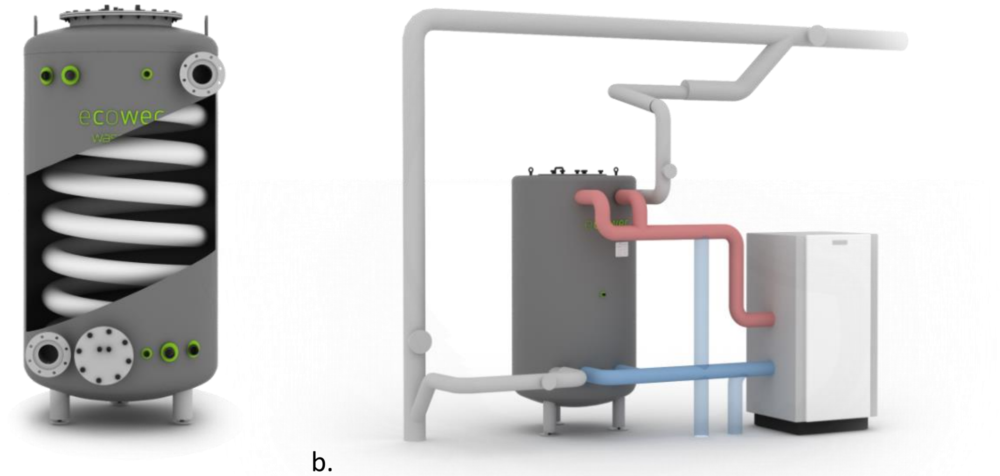
3.3.6 Next steps to reach next TRL

The prototype we used in the Seville site satisfy all the technical request in term of efficiency, power achieve and low inertia but the first restraint we found in the market is the price. It's a good technology and product but is to much particular and only for specific application (high efficiency or low temperature running) and where the customer don't concern the price. We have to work in order to reduce its cost and make it cheaper for a large scale market.

3.4 Component 4: Heat recovery system from Waste Water (WASENCO)

HEAT-LowUP will exploit the potential of sewage water as a residual energy source, by means of a dedicated heat recovery unit (ECOWECTM system). WASENCO is in charge of this development, which is extensively reported in deliverable 2.6.

Figure 32 shows general views of the systems and its possible integration within the existing building facilities.



a. b.

Figure 32: ECOWEC system: (a) drawing of the heat recovery unit, (b) general view of possible integration within the existing heating facilities.

The ECOWECTM system consists of a fluid tank with several available direct-connection ports and one main internal coil or heat exchanger. Different direct-connection ports exist because the system has been conceived as a hybrid heat exchanger, able to integrate different energy sources and loads (sewage water, solar energy, heat pump, Domestic Hot Water (DHW) pre-heating, etc.) However, within the LowUP project the purpose is to demonstrate its potential to recover energy from sewage water and integrate it into a general efficient heating concept (HEAT-LowUP).

In this sense, the internal heat exchanger is devoted to that energy recovery. Sewage water associated to cold water and DHW consumption (toilets, showers, washing, cooking, laundry, etc.) flows inside the coil and exchange heat with the tank fluid (normally at a lower temperature).

According to the general integration solution shown in Figure 32 **¡Error! No se encuentra el origen de la referencia.**b., the sewer pipe is connected to the ECOWEC™ unit, on the ground floor of the building. Wastewater is directed through the SWHR system and can be pumped upward through it if the flow is not possible to connect gravitationally. In cases of possible blockage, wastewater automatically bypasses the ECOWEC™ system via an overflow pipe.

Additionally, the primary circuit of a heat pump can be connected directly to the tank and a domestic water pipe could be connected to optional heat exchangers. Within the LowUP project there is only one load connection (inlet/outlet) that be considered. This connection will allow energy from the ECOWECTM system to be delivered to the main HEAT-LowUP stratified tank. According to foreseeable residual energy availability and operation temperatures, the fluid from the SWHR system is expected to be discharged at the lowest thermal level of the stratification range (25-30 C)

Based on inputs from the manufacturer (WASENCO), there are three different available sizes of ECOWECTM:

- R03, width 550 mm, height 1550 mm, weight 150 kg (empty), 450 kg (full). To be launched 2017.
- R08, width 800 mm, height 2080 mm, weight 430 kg (empty), 1230 kg (full). To be launched 2017.
- R10, width 950 mm, height 2080 mm, weight 500 kg (empty), 1500 (full)

All of them have a dedicated heat exchanger for waste water (included always), as well as optional solutions for domestic water and solar heat (as it was already mentioned).

Figure 33: Final rendered 3D-design of small HWHR.

3.4.1 Sensor selection and physical emplacement

A general explanation about sensors, including their description, operation, and role in both HEAT-LowUP and COOL LowUP solutions can be found in section 3.1.1 of this document, which is, in turn, extracted from deliverable 2.9, section 5.3, deliverable 2.9, Annex 2 and deliverable 4.6, section 2.3.

Deliverable 2.6, section 6 contains a wide and detailed information about the location and installation of all pressure and temperature sensors in laboratory tests, however, deliverable 4.6, section 4.1.5 offers information about the real installation of the WASENCO heat recovery system in the students dormitory of Badajoz (Rucab), describing how the system has been equipped with temperature and flow sensors, in order to monitor the performance and possible expansion of the system, due to temperature variation. In addition, control panels and electric cabinets are directly installed on the wall.

Figure 34. Picture of WASENCO system already installed, showing several instrumentation and control devices attached

3.4.2 Data acquisition

The content here is the same as in section 3.1.2 of this document, applicable for all HEAT Low-UP, COOL Low-UP and HP Low-UP solutions.

3.4.3 Monitoring and recording of the validation parameters

The content here is the same as in section 3.1.3 of this document, applicable for both HEAT Low-UP and COOL Low-UP solutions.

3.4.4 KPI monitoring

The list of the identified KPIs for the heat recovery system (ECOWEC system and heat pump) is shown in Table 11**¡Error! No se encuentra el origen de la referencia.** (available in deliverable 2.9, section 5.1):

Table 11: KPIs detailed for the Heat Recovery System

	KPI			Parameters for the calculation			
System	Symbol	Unit	Description (type)	Symbol	Unit	Previous KPI?	Description and/or comments
ECOWEC system	$P_{ECO,W}$	kW	Thermal power availability from the wastewater source (E)	$m_{w,s,ECO}$	kg/s		ECOWEC source mass flow rate
				$T_{win,s,ECO}$	C		ECOWEC source inlet temperature
				$T_{wout,s,ECO}$	C		ECOWEC source outlet temperature
	$P_{ECO,R}$	kW	Thermal power recovered by the ECOWEC system (E)	$m_{w,l,ECO}$	kg/s		ECOWEC load mass flow rate
				$T_{win,l,ECO}$	C		ECOWEC load inlet temperature
				$T_{wout,l,ECO}$	C		ECOWEC load outlet temperature
	$Q_{ECO,W}$	kWh	Thermal energy availability from the	$Q_{ECO,W}$	kWh		Direct measurement from energy meter

			wastewater source (E)				
	$Q_{ECO,R}$	kWh	Thermal energy recovered by the ECOWEC system (E)	$Q_{ECO,R}$	kWh		Direct measurement from energy meter
	η_{ECO}	-	Seasonal ECOWEC system efficiency (E)	$Q_{ECO,R}$	kWh	Yes	Thermal energy recovered by the ECOWEC system
				$Q_{ECO,W}$	kWh	Yes	Thermal energy availability from the wastewater source
	ε_{ECO}	-	ECOWEC thermal effectiveness (E)	$T_{win,s,ECO}$	C		ECOWEC source inlet temperature
				$T_{wout,s,ECO}$	C		ECOWEC source outlet temperature
				$T_{win,l,ECO}$	C		ECOWEC load inlet temperature
				$T_{wout,l,ECO}$	C		ECOWEC load outlet temperature
Heat pump	$P_{elec,HP}$	kW	Electric power consumed by the HP (E)	$P_{elec,HP}$	kW		
	$P_{therm,HP}$	kW	Thermal power delivered by the HP (E)	$m_{w,HP}$	kg/s		HP water-side mass flow rate
				$T_{win,HP}$	C		HP water inlet temperature
				$T_{wout,HP}$	C		HP water outlet temperature
	E_{HP}	kWh	Electric energy consumed by the HP (E)	E_{HP}	kWh		Indirect calculation from $P_{elec,HP}$
	Q_{HP}	kWh	Thermal energy delivered by the HP (E)	Q_{HP}	kWh		Direct measurement from energy meter
	COP	-	Instantaneous Coefficient of Performance (E)	$P_{elec,HP}$	kW	Yes	Electric power consumed by the HP (E)
				$P_{therm,HP}$	kW	Yes	Thermal power delivered by the HP (E)
	sCOP	-	Seasonal COP of the HP (E)	Q_{HP}	kWh	Yes	Electric energy consumed by the HP (E)
				E_{HP}	kWh	Yes	Thermal energy delivered by the HP (E)

3.4.5 Validation conclusions of the prototype system installed in a real emplacement

The operation of the prototype has been conditioned to the fact that electrical consumption cannot be regulated as function of inlet temperature, so reducing proportionally electricity used for heating water to cleaning setpoint temperature; this has been tested by electric analyser and verified with manufacturer, so no energy saving can be calculated for building.

Nevertheless the unit has been characterized and operated; initially only sewage water was accessing the recovery system, in order to evaluate temperature variation of storage medium (and so recovered and stored energy), while in a second moment also TAP water was introduced in energetic balance of the system.

Here below is represented the profile of characterization without consumption of energy:

Color:	Variable:	Unit:	Operation:
blue	Storage medium	°C	Pulsed operation of sewage:
red	Sewage out	°C	
grey	Sewage in	°C	
Yellow	sewage pump	lt/min	

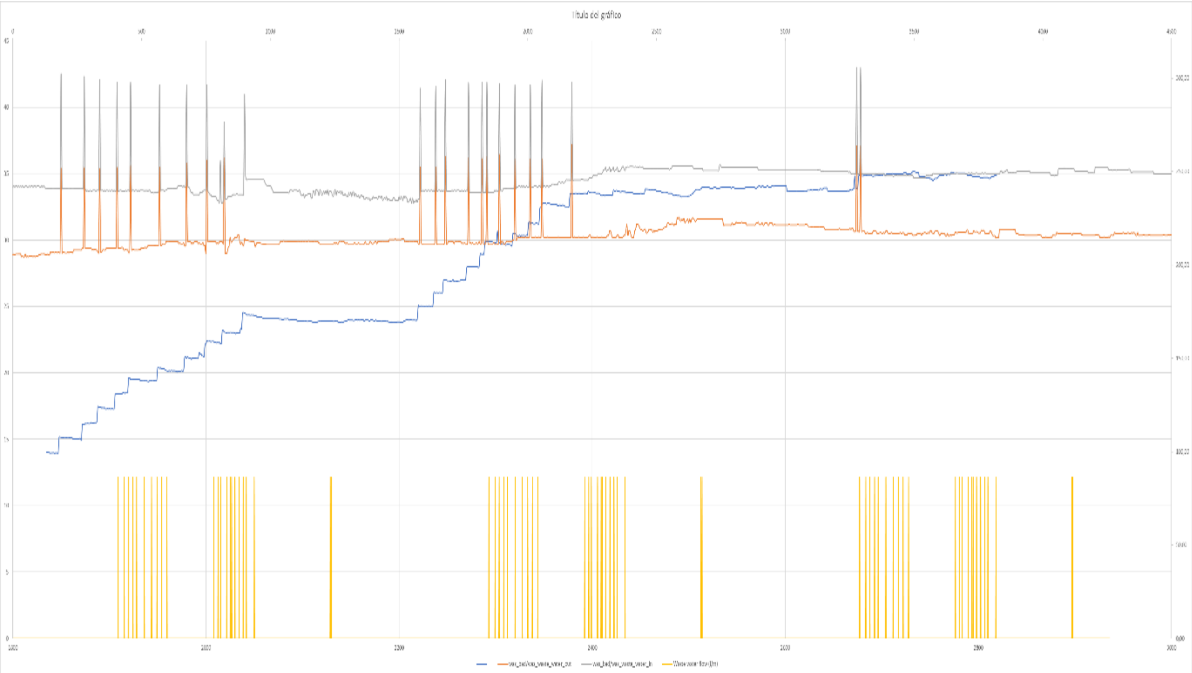


Figure 35 Temperature variation for interior of tank without load

Sewage water enters into the tank with a reduced temperature, with respect to expected when designed at the beginning; furthermore the effect of pumping station is too quick and instable with respect to initial design, so big part of its energy is lost before recovery could happen.

Consumption of dishwasher impulse in recuperation tank TAP water between 13 and 17°C, with frequency similar but reduced flow with respect to sewage (the difference in flow is only contribution of pots). The results is an initial charge of tank energy (for recovering heat from pots and washers) until achieving close to 35°C, even if only at the end of the day.

Following image presents the variation of tank inside temperature for effect of connection of thermal load (TAP water) to sewage recover system.

Color:	Variable:	Unit:	Operation:
blue	Storage medium	°C	Pulsed operation of sewage:
red	Sewage out	°C	
grey	Sewage in	°C	
Yellow	TAP water	lt/min	

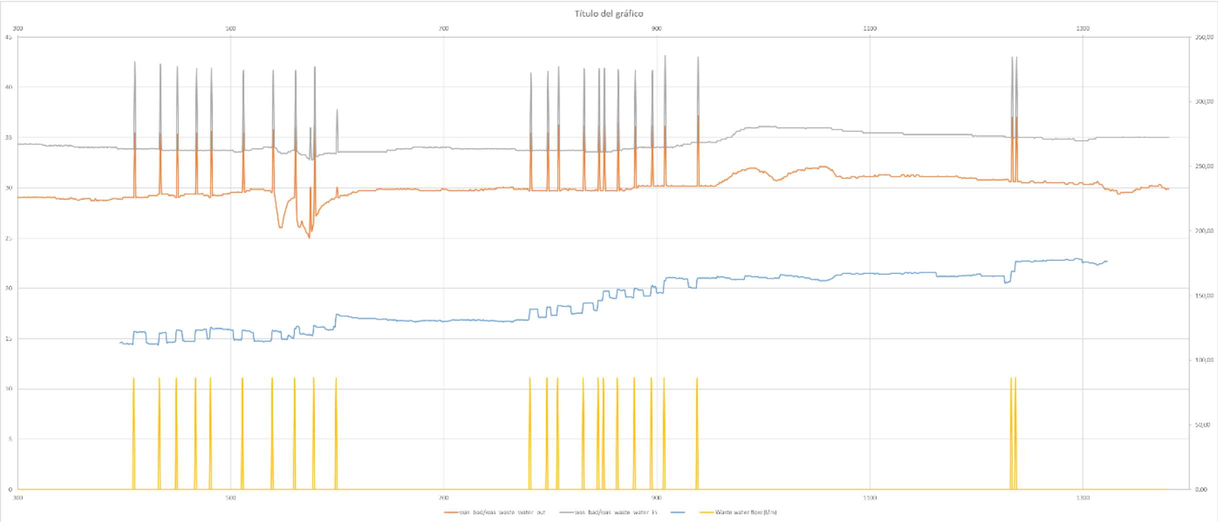


Figure 36: Temperature variation for interior of tank with load

Profile of consumption and production are quite similar from day by day, because of cyclic nature of operation at kitchen. It can be see how tank increase close to 8K for one entire day. The repetitively of cycles keep maintaining the tank in a temperature suitable for HEAT LowUP purposes after about two days, for low temperature (reduced by grease separator and pump station) and for energy recovered (flows extremely quick).

4 Solution 2: Cool-LowUP

4.1 Component 1: ICEBAT – FAFCO

The ICEBAT-FAFCO PCM is a latent cold storage system which allows erasing, decreasing or time shifting the power consumption required for the cooling of buildings or industrial processes

This kind of technology is able to integrate in the same tank these two sources at different temperatures. The tank will be able to collect cooling energy from air & tap water and storing, or equalizing it, according to operation strategies, through a dedicated chiller. This innovative storage system can be charged on favourable periods for cooling generation, even if the thermal levels are close to the operation temperature.

The key objectives of the PCM storage system within the LowUP project are:

- Reduction of 85% on primary energy consumption;
- Reduction of the power consumption of a conventional chiller, and the ROI under 6 years;
- Reduction of energy losses during the transmission of the cooling;
- Increase of the quantity of renewable energy;
- Increase of recovery energy;
- Reduction of operation, investment costs;
- Reduction of CO_2 footprint

Figure 37. PCM tank installed in Seville Demo

The ICEBAT PCP10 model is a steel ice bank, consisting of a rectangular steel tank assembled from trapezoidal steel sheets protected by an acrylic coating and galvanized steel profiles. A vapor barrier is placed between the tank walls and insulation plates to prevent condensation.

A thermal insulation of the walls is guaranteed by 50 to 100 mm plates of an insulating material with a lambda lower than 0.040. PCM tightness of the container is ensured by a liner of synthetic vulcanized rubber, which is resistant to oxidation and heat-aging-. The liner back side is reinforced with textile fibre.

Inside the tank, a metallic structure insures the rigidity of a tubing network. This makes a performant heat exchanger between the water loop and the PCP10 inside the tank. This whole structure, made of galvanized steel is designed on measure for each project, depending on the size of the tank and any mechanical constraints specific to the project.

The equipment is insulated as much as possible, avoiding every condensation problems on the outside wall of the tank. In most projects, the top of the ICEBATs are closed and insulated by top cover sandwich panels (40mm thin), which are removable to allow maintenance or reparation if necessary.

For more detail about the design specifications of this device, see deliverable 2.8.

Concerning the main features and characteristics of this device, in order to have an idea, the range of cooling power capacity that one ICEBAT is able to offer moves between 150 kWh and 18 MWh. After 8 hours of charge, it can deliver partially or completely the cooling energy that it has stored, within 45 minutes or 10 hours. Other technical data and features of the actual LowUP equipment (a 96 kWh FAFCO icebat tank) are hereunder explained:

- Latent storage capacity: 96 kWh
- Max. operating temperature: 40°C
- Max. operating pressure: 3 bar
- Total PCM content: 2218 l
- Solid PCM volume usual charge: 1550 l
- Solid volume of additional PCM: 668 l
- Exchangers content: 130 l
- Approximate shipping weight: 820 kg
- Approximate operating weight: 3187 kg
- Floor area: 3 m^2

The tank is designed to store cool with PMC instead of water, with a specific heat exchanger submerged into the PCM, operating for both charging and discharging through the same water loop. A pump station is installed in order to invert the flow direction according to required operation strategy, while the 2 and 3 ways valves has been designed in order to facilitate the correct circulation of the flow direction and regulate the operating temperature of the system.

Figure 38. PCM tank installed in Seville Demo, showing the installed valves and the instrumentation attached

LowUP

4.1.1 Sensor selection and physical emplacement

A general explanation about sensors, including their description, operation, and role in both HEAT-LowUP and COOL LowUP solutions can be found in section 3.1.1 of this document, which is, in turn, extracted from deliverable 2.9, section 5.3, deliverable 2.9, Annex 2 and deliverable 4.6, section 2.3.

As shown in Figure 39, Figure 40 and Figure 41, the PCM FAFCO technology incorporates two temperature sensors (inlet and outlet) destined to control both charge and discharge cycles of the system:

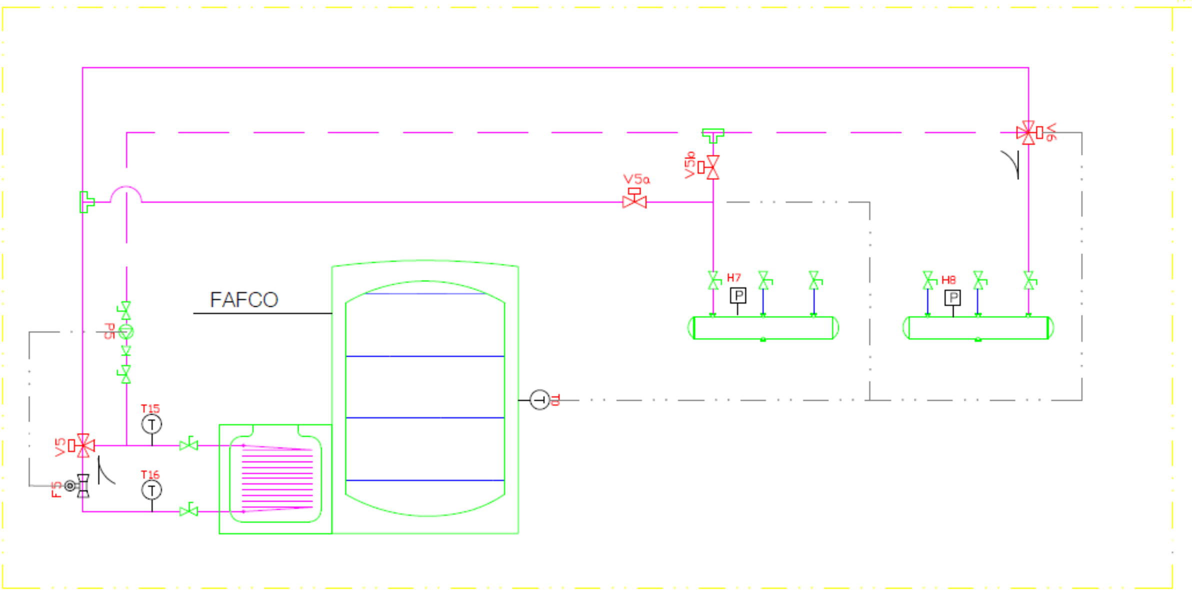


Figure 39. P&ID diagram including the specific connections and instrumentation of the ICEBAT-FAFCO PCM cold storage system at Seville plant

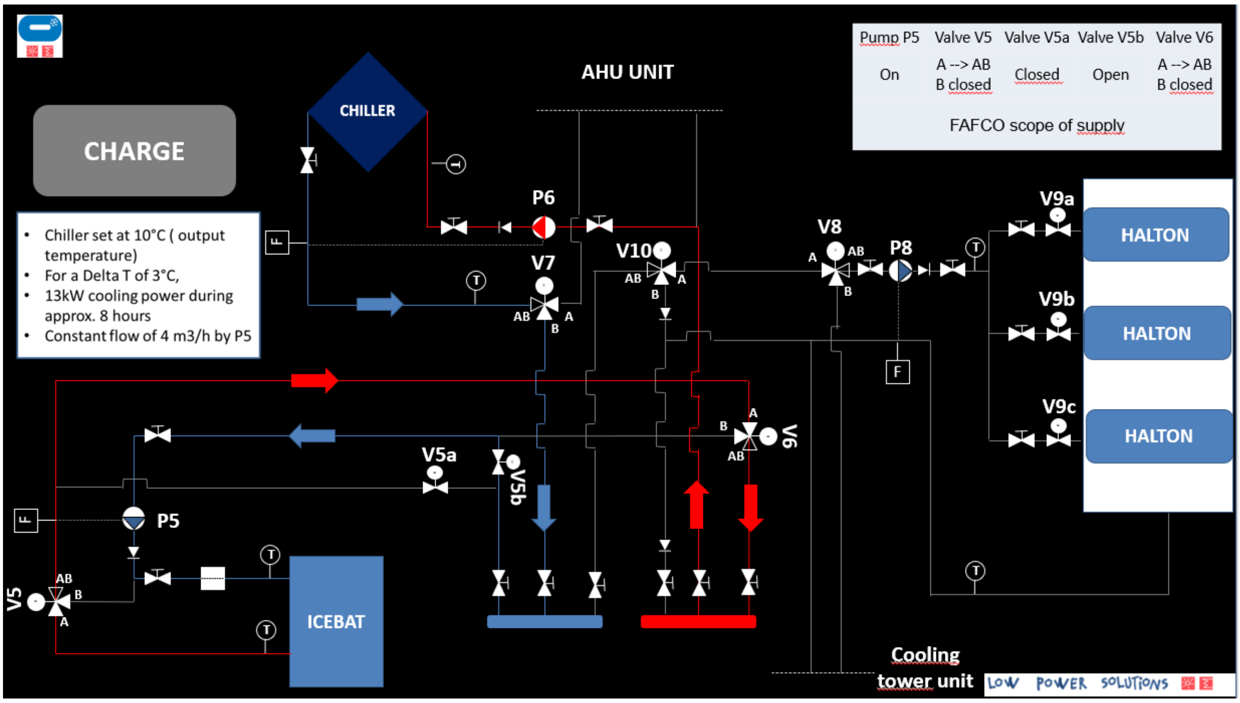


Figure 40. P&ID of charging operation

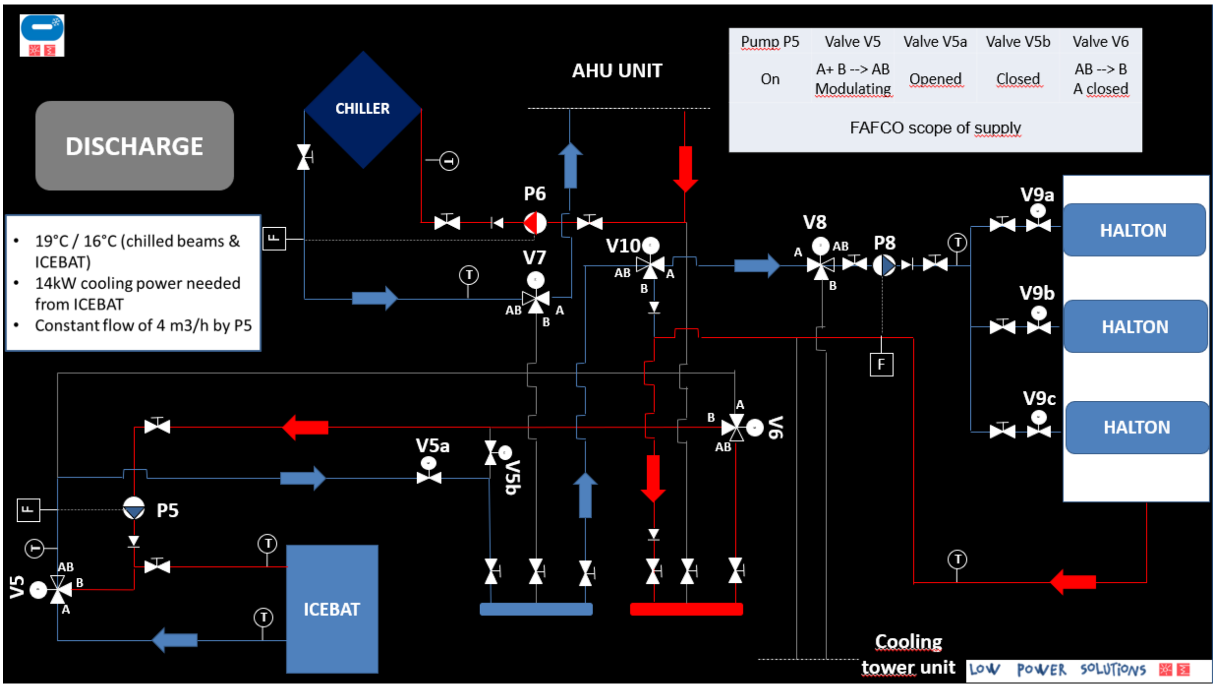


Figure 41. P&ID of discharging operation

Concerning the level, the FAFCO ICEBAT are the only ones on the market to have a real-time monitoring of the load level with 1% accuracy, the system includes:

- A visual indicator of load level, graduated from 0 to 100%,
- An electronic level sensor with a 4-20 mA output compatible with the BMS, monitoring and control systems.

If outside, the sensor and indicator are installed in a protected stainless-steel box. In the following Figure 42 the isolating valves and sensors are displayed for this unit.

Figure 42. Flange isolation valve and sensors.

Finally, as a complement of this information, deliverable 4.6, section 8.3 includes the complete electric and control diagrams for the PCM cooling storage tank in association with the other cooling equipment.

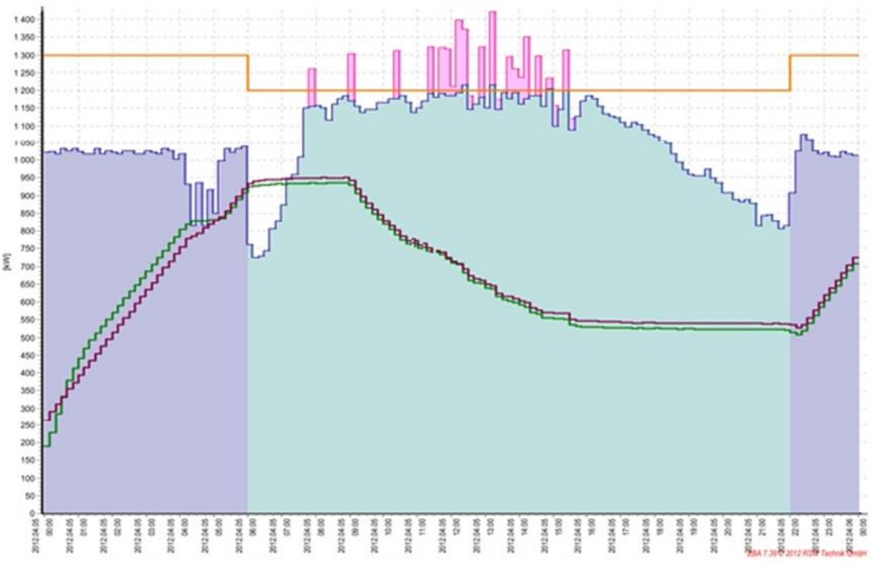
4.1.2 Data acquisition

The content here is the same as in section 3.1.2 of this document, applicable for all HEAT Low-UP, COOL Low-UP and HP Low-UP solutions.

4.1.3 Monitoring and recording of the validation parameters

In principle, some of the contents of section 3.1.3 of this document, is applicable here, in general for both HEAT Low-UP and COOL Low-UP solutions. However, deepening into the FAFCO ICEBATs, these equipment have 3 levels of monitoring and control, in order to improve the performance of the plant and optimize continuously the operation:

- Level 1: On-line Monitoring System, to have permanent access to the operation data, draw graphs and curves with electrical consumptions, ice level, and tariffs,
- Level 2: On-line and automated control system for electrical load management of the customer site,
- Level 3: Multi-sites control system for power management and energy trading



Real data from Institut Curie, Paris, France
on a 24h period

Figure 43: Example of FAFCO monitoring data

4.1.4 KPI monitoring

Monitoring variables should respond to the needs from control, surveillance and evaluation objectives. Therefore, a first definition of the technical Key Performance Indicators (KPIs) was done considering the expected impacts of the project. In deliverable 2.9, section 5.1, the general KPIs for the COOL - LowUP solution are defined:

Table 12: Expected impacts for LowUP building solutions (according to the DoA)

COOL – Low UP expected impact (according to the DoA):
▪ 14% of expected GHG emissions saving (compared with a conventional system) ▪ 25% of total HVAC cooling energy demand covered by renewable energy ▪ 14% of expected primary energy saving (compared with a conventional system)

Table 13: Definition of Key Performance Indicators (KPIs) for the overall COOL-LowUP solution

	KPI			Parameters for the calculation			
System	Symbol	Unit	Description (type)	Symbol	Unit		Description and/or comments
COOL-LowUP system	GHG_S	$kgCO_2eq$	GHG emissions saving compared with a conventional system (G)	η_{CS}	-		Efficiency of the conventional system
				PEF_E	-		Primary energy factor of electricity
				PEF_{CS}	-		Primary energy factor of the final energy consumed by the conventional system
				GHG_{CS}	$kgCO_2eq$		GHG emission factor for primary energy consumed by the conventional system
	PES	kWh	Primary Energy Savings (E)	GHG_E	$kgCO_2eq$		GHG emission factor for electricity

				PEF_E	-		Primary energy factor of electricity
				PEF_{CS}	-		Primary energy factor of the final energy consumed by the conventional system
	P_{aux}	kW	Electric power consumed by auxiliary equip. (E)	P_{aux}	kW		
	E_{aux}	kWh	Energy consumed by auxiliary equipment (E)	E_{aux}	kWh		Indirect calculation from P_{aux}
	f_{CT}	-	Fraction of heat demand covered by cooling tower (ambient air energy source) (E)	Q_{CT}	kWh	Yes	Cooling energy delivered by the cooling tower
				$Q_{total,CB}$	kWh	Yes	Total cooling energy delivered by the chilled beams (air+coil)
	$f_{chiller}$	-	Fraction of heat demand covered by the chiller (renewable or not, depending on sCOP) (E)	Q_{HP}	kWh	Yes	Thermal energy delivered by the HP
				$Q_{fluid,RF}$	kWh	Yes	Thermal energy delivered by the fluid to the radiant floor (i.e. total heat demand)
	f_{REN}	-	Fraction of heat demand covered by renewable energy sources (E)	sEER	-	Yes	Seasonal COP of the chiller (to consider it as renewable energy source or not)
				f_{CT}		Yes	Fraction of $Q_{total,CB}$ covered by ambient air (CT)
				$f_{chiller}$		Yes	Fraction of $Q_{total,CB}$ covered by renewables
	PPDh	%-hour	Cumulated global discomfort indicator (C)	T_{op}	C		Operative temperature
				PPD_{lim}	%		Maximum limit of PPD according to comfort criteria (e.g. from ISO7730)

Next, the list of the identified KPIs for the ICEBAT-FAFCO cooling system is specified in Table 14 (also available in the same deliverable):

Table 14: KPIs detailed for the ICEBAT-FAFCO cooling system

	KPI			Parameters for the calculation			
System	Symbol	Unit	Description (type)	Symbol	Unit		Description and/or comments

Compression chiller	$P_{elec,chiller}$	kW	Electric power consumed by the chiller (E)	$P_{elec,chiller}$	kW		
	$P_{therm,chiller}$	kW	Cooling power delivered by the chiller (E)	$m_{w,chiller}$	kg/s		Chiller water-side mass flow rate
				$T_{win,chiller}$	C		Chiller water inlet temperature
				$T_{wout,chiller}$	C		Chiller water outlet temperature
	$E_{chiller}$	kWh	Electric energy consumed by the chiller (E)	$E_{chiller}$	kWh		Indirect calculation from $P_{elec,HP}$
	$Q_{chiller}$	kWh	Cooling energy delivered by the chiller (E)	$Q_{chilller}$	kWh		Direct measurement from energy meter
	EER	-	Instantaneous Energy Efficiency Ratio (E)	$P_{elec,chiller}$	kW	Yes	Electric power consumed by the HP
				$P_{therm,chiller}$	kW	Yes	Thermal power delivered by the HP
	sEER	-	Seasonal EER of the chiller (E)	$Q_{chiller}$	kWh	Yes	Electric energy consumed by the HP
				$E_{chiller}$	kWh	Yes	Thermal energy delivered by the HP
PCM storage tank***	$P_{PCM,load}$	kW	PCM discharge (load) thermal power (E)	$m_{w,l,PCM}$	kg/s		PCM storage load mass flow rate
				$T_{win,l,PCM}$	C		PCM storage load fluid inlet temperature
				$T_{wout,l,PCM}$	C		PCM storage load fluid outlet temperature
	$P_{PCM,source}$	kW	PCM charge (source) thermal power (E)	$m_{w,s,PCM}$	kg/s		PCM storage source mass flow rate
				$T_{win,s,PCM}$	C		PCM storage source fluid inlet temperature
				$T_{wout,s,PCM}$	C		PCM storage source fluid outlet temperature
	$Q_{PCM,load}$	kWh	Energy discharged from the PCM storage (E)	$Q_{PCM,load}$	kWh		Indirect calculation from $P_{PCM,load}$
	$Q_{PCM,source}$	kWh	Energy charged to the PCM storage (E)	$Q_{PCM,source}$	kWh		Indirect calculation from $P_{PCM,source}$
	P_{coil}	kW	Thermal power delivered by the	$m_{w,CB}$	kg/s		Fluid mass flow rate at the CB coil

Chilled Beams conditioning system			fluid at the coil (E)	$T_{win,CB}$	C		CB coil fluid inlet temperature
				$T_{wout,CB}$	C		CB coil fluid outlet temperature
	P_{air}	kW	Thermal power delivered by the primary airflow (E)	m_a	kg/s		Primary air mass flow rate
				$T_{a,in}$	C		Inlet air temperature at the AHU
				$T_{a,out}$	C		Outlet air temperature at the AHU
	$P_{total,CB}$	kW	Total thermal power delivered by the chilled beams (air+coil)	P_{coil}	kW	Yes	Thermal power delivered by the fluid at the coil
				P_{air}	kW	Yes	Thermal power delivered by the primary airflow
	$Q_{total,CB}$	kWh	Total cooling energy delivered by the chilled beams (air+coil)	$Q_{total,CB}$	kWh		Indirect calculation from $P_{total,CB}$

4.1.5 Results validation of the prototype system installed in a real emplacement

The system has been designed for operating according to chiller charging conditions and chilled beam discharged conditions; this means that inlet temperatures for charging and discharging move within a small controlled range (chilled beams require fixed temperature and PCM requires chilled fixed temperature).

In next figure are represented both phases of operation: charging with chiller and discharging with chilled beams. The different boxes highlight different moment of operation; it must be stated that the chiller wasn't stopped when PCM tank achieved its limit of capacity: charging in blue box, charging with saturation in green box and discharging in red box.

Color:	Variable:	Unit:	Operation:
Violet	Chilled water out	°C	Pump at constant nominal flow
Green	Chilled water in	°C	
Blue	Tank operation	mode	
Red	Water flow	°C	

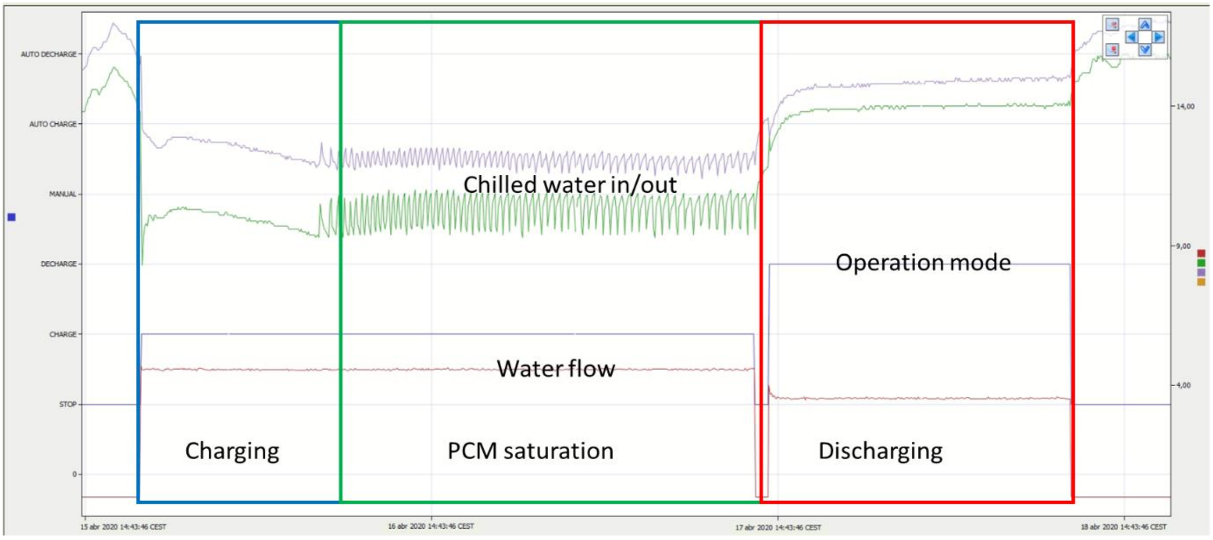


Figure 44. Different phases of operation for PCM tank

During charging, chiller starts operation and gradually wins thermal inertia of the system, delivering chilled water at 11°C to tank which stores cooling, maintaining a constant delta T° between inlet and outlet (blue box).

Once PCM is saturated (fully charged) energy required from chiller is zero, so compressor start and stops with the purpose of maintaining constant temperature inside water loops, which are recirculating water through tank (green box) even if not necessary.

During discharging, due to plumbing pressure drops reasons, flows reduces a bit still but maintaining minimum requirements of tank; it can be seen how temperatures are maintained constant with stable Delta T° until achieving empty of tank (end of red box). Next image shows regulation of outlet 3ways valve to supply chilled water at constant temperature to chilled beams.

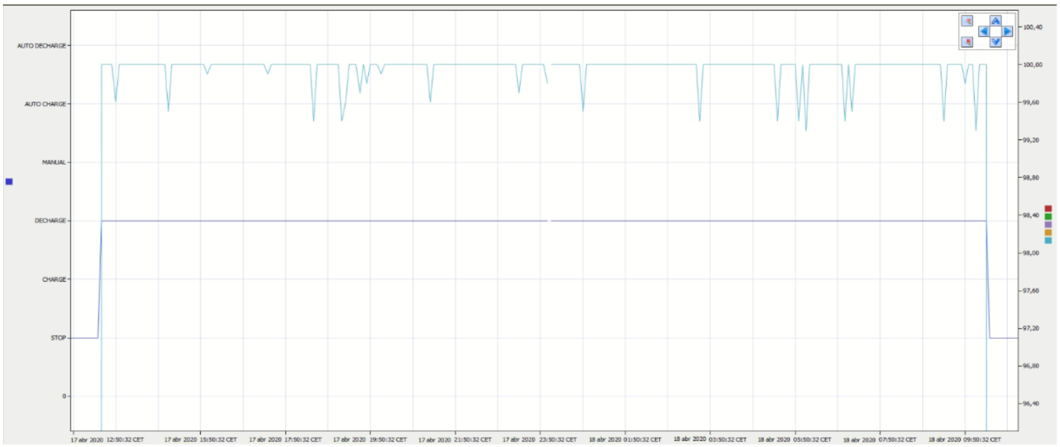


Figure 45. Operation of 3ways valve over PCM tank outlet temperature

Mixing valve outcoming from the tank, used for supplying setpoint temperature during discharge, allow maintain operation temperature of PCM optimal independently from possible peak of charge that would reduce designed working conditions, affecting long term stability of the storage medium.

4.2 Component 2: Chilled Beams

The chilled beams are used as terminals for ventilation and cooling within the office building + warehouse; they are integrated with adaptive lightning and a temperature regulation system in order to provide total comfort for the end users. These devices are feed with air from the AHU and with cold water from tank/chiller. HALTON is the responsible company that manufactures this technology.

Figure 46. Chilled beams installed inside the office

The active chilled beams cooling system works with tailored coils, in order to operate close to the set point conditions and to efficiently fulfil the cooling load of the building when operating at higher temperature (>18°C) respect to traditional chilling solutions.

Beams work with fixed water temperature and fixed air pressure incoming to the coils; the 2 ways valves embedded in the case regulate the flow according to office cool requirements (temperature) while embedded dampers regulate air flow in function of the thermal load of the building. Halton control manages opening of both in function of the setpoint defined by user, activity and number of persons present in the building.

The technical information for the installation is here presented:

Office room + Warehouse		
SUPPLY AIR		
Chilled beams Office room	**8**	
Chilled beams Warehouse room	**3**	
distance between beams in Warehouse	3660	mm
Static pressure beams	104	Pa
Supply air flow, boost	399	l/s
Office room each beam	42	l/s
Warehouse each beam	21	l/s
Supply duct size round diameter	400	mm
Supply duct velocity	3.2	m/s
Supply air flow, normal	255	l/s
Office room each beam	24	l/s
Warehouse each beam	21	l/s
Supply duct size round diameter	400	mm
Supply duct velocity	2.0	m/s
Supply air flow, min	103	l/s
Office room each beam	5	l/s
Warehouse each beam	21	
Supply duct size round diameter	400	mm
Supply duct velocity	0.8	m/s

Figure 47. Calculation for chilled beams system

More information about these devices, including design criteria, manufacturing, energy efficiency and techno-economic analysis can be found in deliverable 2.4

4.2.1 Sensor selection and physical emplacement

A general explanation about sensors, including their description, operation, and role in both HEAT-LowUP and COOL LowUP solutions can be found in section 3.1.1 of this document, which is, in turn, extracted from deliverable 2.9, section 5.3, deliverable 2.9, Annex 2 and deliverable 4.6, section 2.3.

As described deliverable 4.6, section 2.2.3 The chilled Beams work with fixed water temperature and fixed air pressure incoming in the coils; the 2 ways valves embedded in the case regulate the flow according to the cooling requirements of the office (temperature) while embedded dampers regulate the air flow depending on the thermal load of the building. Halton control manages both systems in function of the human activity (number of people present inside the building) and the set point defined by the user.

Each beam is completed by its own control system for water, air and light; both temperature and luminosity sensors are used to regulate temperature and light intensity, according to the set points coming from the remote PLC manager.

The following Figure 48 shows in detail a PLC for a chilled beam

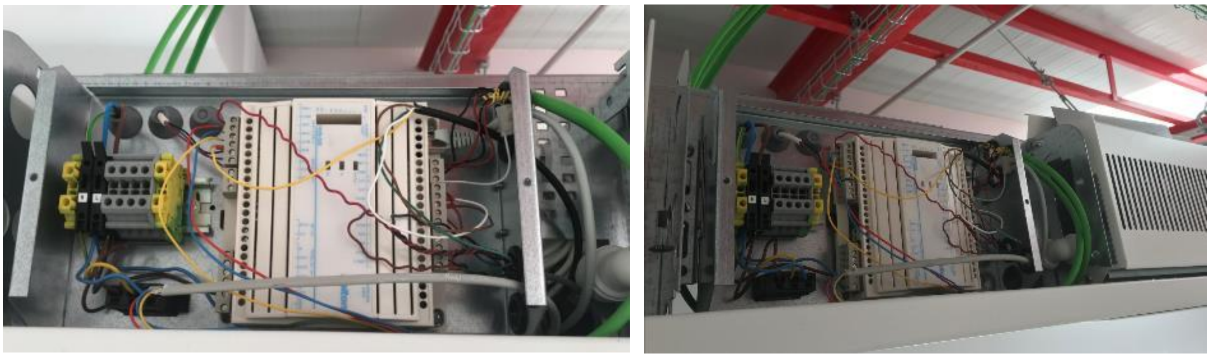


Figure 48. Control panel in a chilled beam.

4.2.2 Data acquisition

The content here is the same as in section 3.1.2 of this document, applicable for all HEAT Low-UP, COOL Low-UP and HP Low-UP solutions.

4.2.3 Monitoring and recording of the validation parameters

The content here is the same as in section 3.1.3 of this document, applicable for both HEAT Low-UP and COOL Low-UP solutions.

4.2.4 KPI monitoring

The list of the identified KPIs for the chilled beams is shown in Table 15 (available in deliverable 2.9, section 5.1):

Table 15: KPIs detailed for the Chilled Beams cooling system

	KPI			Parameters for the calculation			
System	Symbol	Unit	Description (type)	Symbol	Unit		Description and/or comments
Chilled Beams conditioning system	P_{coil}	kW	Thermal power delivered by the fluid at the coil (E)	$m_{w,CB}$	kg/s		Fluid mass flow rate at the CB coil
				$T_{win,CB}$	C		CB coil fluid inlet temperature
				$T_{wout,CB}$	C		CB coil fluid outlet temperature
	P_{air}	kW	Thermal power delivered by the primary airflow (E)	m_a	kg/s		Primary air mass flow rate
				$T_{a,in}$	C		Inlet air temperature at the AHU
				$T_{a,out}$	C		Outlet air temperature at the AHU
	$P_{total,CB}$	kW	Total thermal power delivered by the chilled beams (air+coil)	P_{coil}	kW	Yes	Thermal power delivered by the fluid at the coil
				P_{air}	kW	Yes	Thermal power delivered by the primary airflow
	$Q_{total,CB}$	kWh	Total cooling energy delivered by the chilled beams (air+coil)	$Q_{total,CB}$	kWh		Indirect calculation from $P_{total,CB}$

4.2.5 Results validation of the prototype system installed in a real emplacement

Focus of the R&D work done by Halton during last year of LowUP project:

1. To commission and to study Cool LowUP chilled beam system at Acciona demonstration building, and to further improve system with Acciona. After that additional components were provided by Halton to chilled beam system and integration/testing done at Acciona was supported from Halton. Also various co-operation work with LowUP partners was done.
2. To research and develop Halton variable airflow chilled beam system of Cool LowUP for reaching next TRL and CRL levels

Main work done for variable airflow chilled beam system for reaching next TRL and CRL levels during last year of LowUP project for getting real business impact of work done in LowUP project has been:

- Renewing control platform in chilled beam system and including there connection to Halton cloud for making integration to partners' systems easier. This work is still continuing and will be finalized during 2021. After that connection can be done in BacnetIP level or through Halton Edge gateway more standardized way. The automation diagram of model solutions of the system are presented in Figure 3 and 4.
- Clearly productizing the system further to increase TRL and CRL with all room, zone and central sub-systems. This includes different demand based room units where exposed variable airflow chilled beam is one key solution. Also other components tested in LowUP project are being productized like zone dampers. There measurements in laboratory and co-operation with controller manufacturing has been done for validating pressure measurements with low airflow rates. This is needed to be reached according to new European building regulations for minimizing energy usage in buildings with accurate variable airflow ventilation systems. This includes calculation models and tools for design and operation of the chilled beam system. Visualization of variable airflow exposed chilled beams done at Halton in office and meeting room setups presented in Figure 5 demonstrates the adaptability of the chilled beam system with constant static pressure ductwork concept (based on model designs done with HVAC design tool AutoCad Revit).

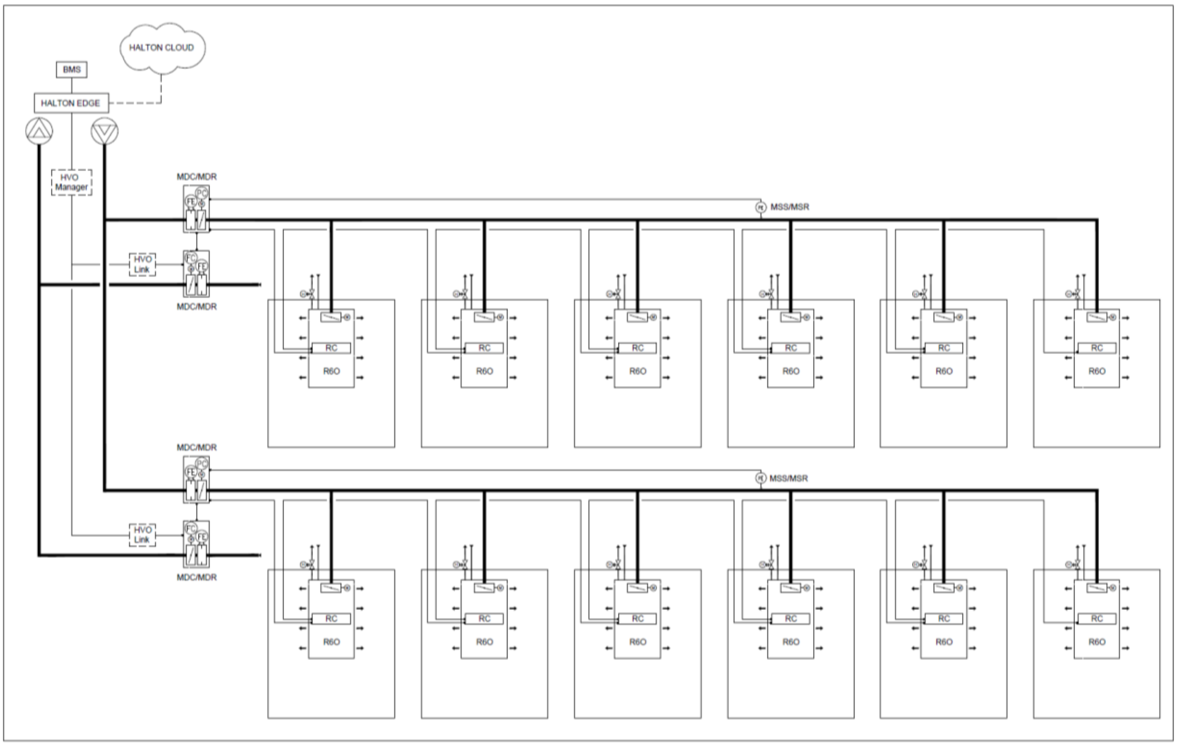


Figure 49. Chilled beam system level automation diagram including different ventilation components, controllers and cloud connection.

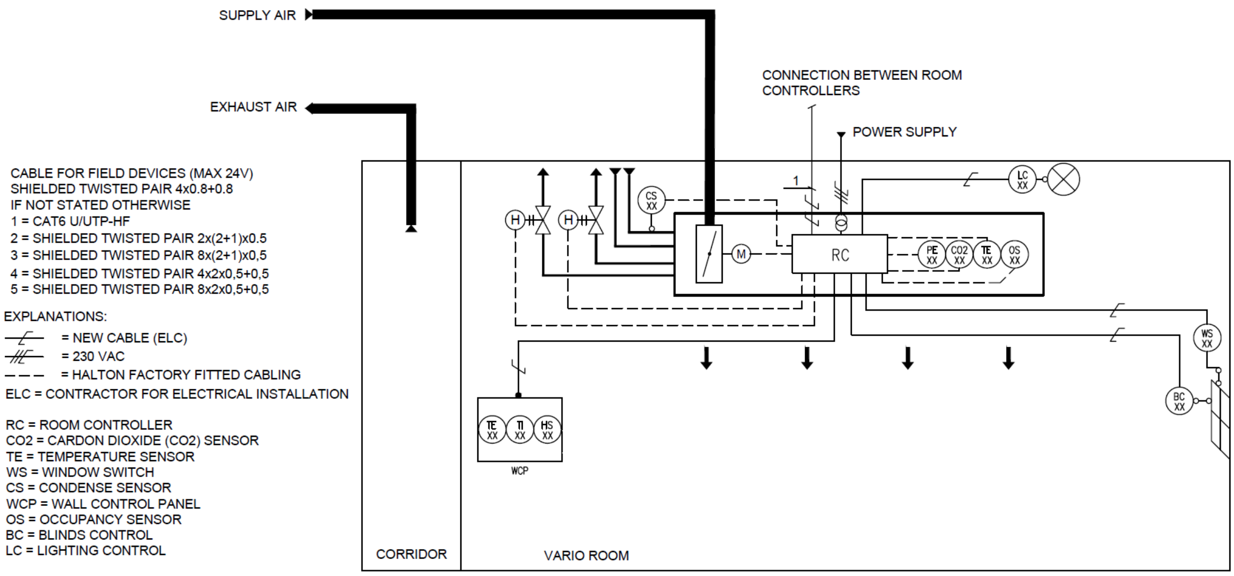


Figure 50. Example of developed automation model design with variable airflow chilled beam in cooling and heating with central exhaust. These will be part of productized room system package including HVAC and building automation.

Figure 51. Photorealistic visualization prepared by Halton during last year of LowUP project based on model designs with HVAC design tool AutoCad Revit demonstrating adaptability of novel variable airflow exposed chilled beam system to adapt easily to different space usage in office buildings

As it is described in deliverable D2.4, the chilled beam system in the test office building will be commissioned by Halton. Different tests will be carried out for ensuring the proper operation the chilled beam system. The chilled beam system based on static pressure ductwork is much faster to commission than traditional ductwork especially in the big office buildings.

4.2.6 Next steps to reach next TRL

Future technology development strategy will be based on core system offering including system components tested in LowUP project. Target of this development is to ensure reliable functioning of the indoor climate systems provided by Halton and be able to integrate partners' smart building systems. After that the chilled beam system with these components can be efficiently manufactured and designed for customer projects. Target is to launch this system offering in 2021.

5 Solution 3: HP-LowUP

5.1 Component 1: HP-GEA (D3.2, D4.13 y D4.15)

The design improvement of the GEA heat pump is based on the industrial needs of low carbon heating using the available heat sources. During the LowUP project GEA considered all aspects of the heat pump design, in order to optimise the overall system and increase its efficiency and competitiveness.

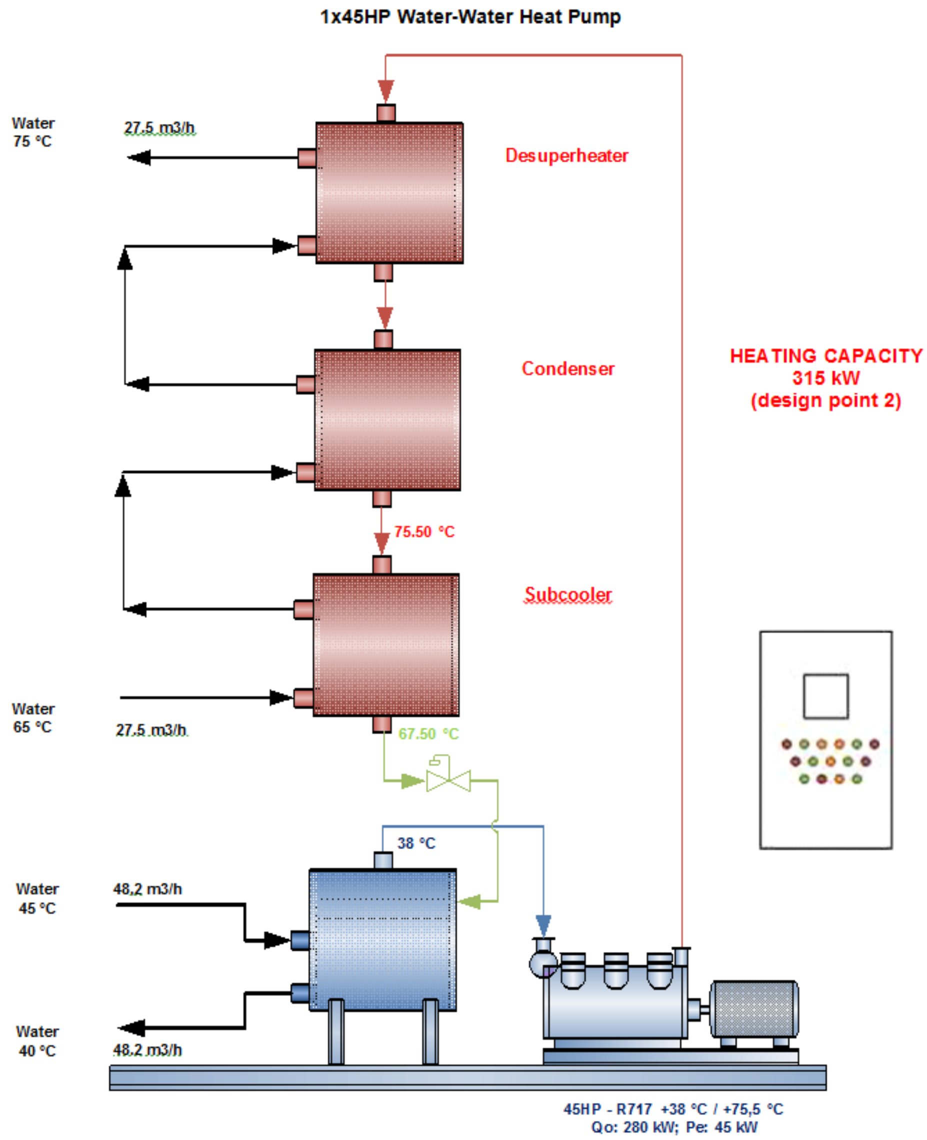


Figure 52: Diagram of the LowUP Heat Pump

For the LowUP project, a 45HP compressor (1200 rpm) heat pump device was chosen. For the validation, the heat pump has been installed in a demonstration site in Seville, where it will be possible to test the heat pump at different running conditions.

The selected compressor is a Grasso piston compressor, which refrigerating capacity and shaft power agrees with EN12900 and EN13771. The system ensures a maximum of 1 bar pressure drop.

R-717 (Ammonia) was chosen as the main refrigerant, due to its good performance for high temperature systems.

The heat pump is designed to be installed in a container with a minimum temperature of 15^{0}C and a maximum of 40°C. The container will be fitted with normal ventilation and emergency ventilation, so the plant room will be kept safe during the test.

Figure 53: Picture of the LowUP Heat Pump

Following the development realized during previous WPs and, according to results achieved during manufacturing, installation, commissioning and operation, a sensible conclusion about the readiness of the prototype systems and components will be carried out at process level, in order to prove the industrial potential and its integration within the energy system. In this regard, the following methodology gives an advice about the main actions carried out and their actual development:

5.1.1 Sensor selection and physical emplacement

Firstly, deliverable D3.4, section 5.3 distinguishes between sensors and actuators, defining them, explaining their purpose and their grade of implementation and development within the overall HP-Low UP system.

Secondly, Annex 1 of deliverable D3.3 contains technical information about all the equipment already installed during the design & manufacturing process of the heat pump (sensors, instruments, controllers…etc, deliverable D3.3, section 2.2.6)

- Coils for solenoid valves
- Regulating valves
- Flow Switches
- Pressure, temperature and level transmitters

5.1.2 Data acquisition

The content here is the same as in section 3.1.2 of this document, applicable for all HEAT Low-UP, COOL Low-UP and HP Low-UP solutions.

5.1.3 Monitoring and recording of the validation parameters

Done and described in the following sections:

- Deliverable 3.4, section 5.2: At this point, a first approximation about the control and monitoring method of the entire process is made, presenting the monitoring variables that should be measured for each of the technologies involved within the HP-LowUP industrial waste heat recovery & upgrading solution.

Variables and signals are classified according to their scope and the input/output approach from the local PLCs perspective. Thus, the following categories should be considered:

- Local inputs: They are low-level input variables for the local PLCs received from sensors.
- Local outputs: They are low-level output variables for the local PLCs that need to be communicated to actuators in order to make control actions effective.
- Global inputs: They are high-level input variables for the local PLCs received from the Frontend PLC. They will normally correspond to setpoint information and will be communicated through Modbus protocol
- Global outputs: They are output variables for the local PLCs that will be sent to the Frontend PLC. Normally they will correspond to signals that transfer data registered by the sensors, but translated to Modbus protocol.

The figure below shows a very simple sketch of this approach:

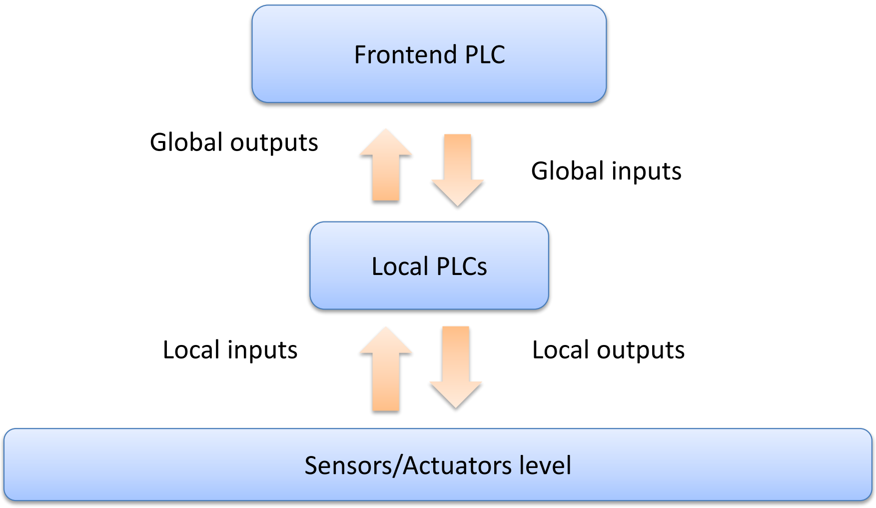


Figure 54: Classification and basic schema of control and monitoring variables

- Deliverable 3.4, section 4.4: refers to the LowUp manager, which will communicate all software modules developed in the project and will orchestrate their communication as well as the communication with external software modules like the SCADA, any external database, and the embedded PC's of the external demo sites.
- Deliverable 4.5, section 4.2.3: talks about the heat pump's control system installed at the real demo site emplacements (Madrid, Setúbal and Gipuzkoa), detailing the following parts:

  - The Omni system: this is the own control system of the heat pump. There, the setpoints desired for each experiment will be introduced. The system is able to monitor and register all the variables needed for the characterisation, and allows some advanced control features, such as fix the working power load fraction

- Laboratory setup: is the centralized control system of the laboratory. As for the control aspects, each of the elements has its own control system, and can, therefore, operate autonomously for a given set point. Additionally, laboratory counts with a centralised control system called Delphin all the operating variables are monitored in the SCADA of the laboratory, which allows the equipment to be operated remotely. Here, the heat pump is integrated into Delphin, through the SCADA monitoring system

- Deliverable 3.4, Annex 1: The monitoring variables that should be measured for each of the technologies involved within the HP-LowUP industrial waste heat recovery & upgrading solution are here listed. They allow defining the theoretical main specifications and requirements for the measuring devices to be used in LowUP implementation within WP4. Concerning the heat pump, our Table 16 here (extracted from Annex 1, Table 5) shows all control variables (Local inputs and outputs) for this device.

Table 16: Control variable list for the high efficiency heat pump GEA

Name	Unit	Signal	Range min.	Range max.	Description and remarks
LOCAL OUTPUTS					
Pump speed	%	Analog 4-20 mA	0	100	velocity of the pump depending on temperature (CS)
Pump On/Off		Digital PFC			pump switching On/Off (CS)
Pump speed	%	Analog 4-20 mA	0	100	velocity of the pump depending on temperature (HS)
Pump On/Off		Digital PFC			pump switching On/Off (HS)
LOCAL INPUTS					
CS Water inlet temperature	°C	Analog RTD	-200	850	Water inlet temperature at the heat pump (CS)
CS Water outlet temperature	°C	Analog RTD	-200	850	Water outlet temperature from the heat pump (CS)
HS Water inlet temperature	°C	Analog RTD	-200	850	Water inlet temperature at the heat pump (HS)
HS Water outlet temperature	°C	Analog RTD	-200	850	Water outlet temperature at (HS)
Compressor suction pressure	bar	Analog 4-20 mA	0	30	NH3 suction pressure
Compressor discharge pressure	bar	Analog 4-20 mA	0	60	NH3 suction pressure
Compressor oil pressure	bar	Analog 4-20 mA	0	30	Oil pressure
Compressor crankcase pressure	bar	Analog 4-20 mA	0	30	NH3 pressure in crankcase
Compressor suction temperature	°C	Analog RTD	-200	850	NH3 gas temperature in compressor suction
Compressor Discharge temperature	°C	Analog RTD	-200	850	NH3 gas temperature in compressor discharge
Compressor oil temperature	°C	Analog RTD	-200	850	Oil temperature in compressor
Compressor motor speed	°C	Analog TCP/IP	0	1500	Motor rotation speed value from VFD
Suction pipe temperature	°C	Analog RTD	-200	850	Suction pipe temperature
Oil Vessel temperature	°C	Analog RTD	-200	850	Oil temperature for oil recovery system
Engine room temperature	°C	Analog RTD	-200	850	Ambient temperature where HP is located
NH3 detection in HS water circuit	pH	Analog 4-20 mA	0	14	PH measurement
NH3 detection in CS water circuit	pH	Analog 4-20 mA	0	14	PH measurement
GLOBAL OUTPUTS					

Pump speed	rpm	Discrete TCP/IP	0	3000	velocity of the pump depending on temperature (CS)
Pump On/Off		Digital TCP/IP			pump switching On/Off (CS)
Pump speed	rpm	Discrete TCP/IP	0	3000	velocity of the pump depending on temperature (HS)
Pump On/Off		Digital TCP/IP			pump switching On/Off (HS)
CS Water inlet temperature	°C	Discrete TCP/IP	-200	850	Water inlet temperature at the heat pump (CS)
CS Water outlet temperature	°C	Discrete TCP/IP	-200	850	Water outlet temperature from the heat pump (CS)
CS Water mass flow	m^3/h	Discrete TCP/IP	-200	850	Water volumetric flow rate (CS)
HS Water inlet temperature	°C	Discrete TCP/IP	-200	850	Water inlet temperature at the heat pump (CS)
HS Water outlet temperature	°C	Discrete TCP/IP	-200	850	Water outlet temperature at (CS)
HS Water mass flow	m^3/h	Discrete TCP/IP	0	40	Water volumetric flow rate (CS)
Alarm		Discrete TCP/IP			HP alarm
Warning		Discrete TCP/IP			HP warning
Energy consumption (Electricity)	kWh	Discrete TCP/IP			Energy consumption from the HP (Complete HP package)
Internal control variables (T/p)		Discrete TCP/IP			Variables about ammonia conditions during operation
Energy consumption (Electricity)	kWh	Discrete TCP/IP			Energy consumption (compressor motor)
COP Instantaneous		Discrete TCP/IP			Instantaneous COP calculated internally by the HP
Vibration Analysis		Digital TCP/IP			Vibration analysis
GLOBAL INPUTS					
Water outlet temperature setpoint (HS)	°C	Discrete TCP/IP	20	80	Water outlet of the heat pump setpoint (HS)
Heat pump - On/Off		Digital TCP/IP			switching on/off of the system

5.1.4 KPI monitoring

- Previously, deliverable 3.3, section 2.2 refers to several variables like overpressure of the hot water circuit, operating limits, design conditions, and compressor´s operation margins, all of them already defined during the manufacturing and design phases
- Deliverable 3.4, section 5.1: explains about the Key Performance Indicators (KPIs), in order to design the monitoring network and identify what should be measured and for what purpose. The following Table 17, extracted from deliverable D3.4 is a previous step, in which the different subsystems and their objectives are listed. Concerning the heat pump, the goals are clearly defined:

Table 17: Expected impacts for the heat pump of the HP-LowUP industrial solution

System	Objective
High efficiency electrically driven heat pump	▪ 100% thermal powered system ▪ Recovery of waste heat at 20-45°C ▪ Production of process heat up to 80°C ▪ Seasonal COP over 6 (10% more efficiency than conventional heat pump).

	▪ Temperature lift of 35°C

Therefore, the KPIs for the heat pump device are later defined in

Table 18, which is extracted as well from Table 3 in deliverable D3.4.

Table 18: Definition of Key Performance Indicators (KPIs) for the heat pump of the HP-LowUP industrial solution

	KPIs			Parameters for calculation		
System	Symbol	Unit	Description	Symbol	Unit	Description
Heat Pump (HP)	PE_{HT}	kW	Instantaneous electric power consumed by the HT (E)	-	-	Directed measurement from an electric power and energy meter
	EE_{HT}	kWh	Total electric energy consumed by the HT (E)	-	-	Directed measurement from an electric power and energy meter
	PQd_{HP}	kW	Instantaneous thermal power delivered by the HP (E)	-	-	Direct measurement from energy meter
	EQd_{HP}	kWh	Total thermal energy delivered by the HP (E)	-	-	Direct measurement from energy meter
	COP	-	Instantaneous coefficient of performance of the HP (E)	PE_{HP}	kW	Instantaneous electric power consumed by the HP
				PQd_{HP}	kW	Instantaneous thermal power delivered by the HP
	sCOP	-	Seasonal coefficient of performance of the HP (E)	EEHP	kWh	Total electric energy consumed by the HP
				EQd_{HP}	kWh	Total thermal energy delivered by the HP
	ΔT_{RS}	K	Temperature lift between the wastewater stream and the stream where the thermal energy is delivered by the HP (E)	T_{HPC1}	°C /K	Inlet temperature of the cold fluid
				T_{HPC2}	°C /K	Outlet temperature of the cold fluid
				T_{HPH1}	°C /K	Inlet temperature of the hot fluid
				T_{HPH2}	°C /K	Outlet temperature of the hot fluid

5.1.5 Validation conclusions of the HP prototype and to reach next TRLs

The main goal of the LowUP project is to increase the capability of the systems integrating the different energy equipment in order to exploit low-grade energy sources at building and industrial environments, as effectively and smartly as possible. This objective covers not only technological advances, but the future replicability in other type of buildings and industrial environments as well.

Going deep into the HP-LowUp solution, and without losing perspective of the main goal, the objective covers the development of a unique heat pump range. Whereas the ammonia compressor technology has many advantages in regards to the efficiency and reachable temperatures, there are several aspects of the industrial heat pump range which still can be improved to optimise the design of the heat pump solution.

In this trend, GEA focused the development of 6 specific new improvements that have been already added to the existing industrial heat pump technology of the LowUp project, with the aim of lower the cost and improve efficiency, making the heat pump more attractive to a broader type of applications:

- Injector

  Traditionally, the evaporator (which is still a special heat exchanger adapted for boiling) was fed by gravity flow, accumulating the refrigerant in liquid phase (ammonia, in this case) at the bottom of the equipment. The ammonia absorbs the energy from the cold water circuit and boils away, re-starting the heat pump cycle. However, a great accumulation of liquid into the evaporator decreases the efficiency of the system and increases the risk of possible problems and failures.

  For the LowUP Project, the decision was to introduce an injector system, which takes the liquid from the bottom of the evaporator and reinjects it into the heat exchanger, increasing the turbulent flow and improving the heat transfer, leading to the subsequent reduction of the ammonia charge inside the evaporator. As there is no pump creating a liquid recirculation, the flow should be produced by the venturi effect created by the liquid/gas injected from the expansion valve, in order to drag the liquid from the bottom of the heat exchanger and bring it back into the top of the heat exchanger.

  Although this new improvement was previously proved into the GEA chillers, this is the first time that it is added into the GEA heat pump system. Furthermore, it is unknown what effect could occur due to the different density of the heat pump´s refrigerant, which is not the same as for the chillers. Therefore, the innovation level here could be considered around TRL4.

  After successful tests in ‘s-Hertogenbosch the new injector system was proved and further implemented on other heat pump installation. It is not proved across multiple applications yet, so at the moment it is considered TRL7-8, but the inclusion and standardization of this improvement in the heat pump system is expected soon.

- Heat exchanger design (evaporator)

  After the implementation of the injector system, a revision of the heat exchangers design (specially the evaporator) was necessary. GEA have developed her own unique plate design for the chiller range, which had not been previously proven in any heat pump application. The LowUp project gave the opportunity to implement this plate design into a heat pump and evaluate the results. It is a satisfaction to verify how the new evaporator heat exchanger equipment does not allow liquid carried over to the compressor, fulfilling the expected performance. Since these elements were not previously proved for heat pumps (TRL4) and they are actually being implemented, we can conclude that an advance from TRL 4 to TRL 8 was produced.

- Expansion valve control

  Traditionally the expansion valve has been regulated based on the subcooling liquid after the condenser, so the valve was fully open when 2K subcooling was achieved and fully closed at 0K. This regulation requires some accumulation of liquid inside the condenser, in order to achieve subcooling, which lowers the efficiency. For the LowUp project, a regulation of the expansion valve according to the load of the compressor was introduced.

In addition, in order to improve the regulation, the sloped pipe includes several liquid level controls (switches), introducing a fine tuning control after the condenser. If no liquid is detected, the lower switch located just before the expansion valve closes it. On the other hand, if some liquid is detected, the upper liquid switch fully opens the expansion valve.

Some issues appeared during Tecnalia´s tests, but during the tests in 's-Hertogenbosch this control concept was finally proved. It will be introduced now in the new heat pumps, moving from TRL 3-4 to TRL 7.

- Oil return system

  In order to save costs, the oil return system was changed to the same type as used for the GEA chiller products range. At first, this system was not possible to be tested at Tecnalia installations, but it worked satisfactorily in 's-Hertogenbosch, moving the from TRL 4 to TRL 8-9.

- Vibration sensors

  Vibration sensors on the motor and compressor were added, in order to early detect wears of the bearings. However, the heat pump did not operate long time enough to get any useful data, so further work and research in this direction will be conducted to investigate. TRL4 is still at this phase.

- Control system

  The control system constitutes another of the important advances for the overall HP-LowUP technology, concretely the approach reported in deliverable 3.4 sustains the development of detail engineering and enables to tackle additional important challenges through, like the automatic operation of novel solutions for building conditioning and industrial waste heat recovery without the supervision of a human being, the optimization of the energy generation according to weather forecasting, the energy storage for later uses, and the prediction of breakdowns and possible system failures. This monitoring and control architecture has been thought with particular focus on future replicability of all the LowUP solutions in as many as possible similar facilities. Concerning the GEA heat pump, with the aim of improve its control and include more auxiliary items into the controlling system like water pumps, the PLC controller from Siemens was substituted by a Windows based industrial PC (OMNI) controller. This kind of technology includes more options for logging data and analysing historical data. This is a significant help in terms of maintenance and longevity of the heat pump. This measurement has already been implemented on all heat pumps, moving from TRL4 to TRL 9

All these changes improved significantly the overall COP, which has been improved from the standard average of 5.4 to an average of 6.0 for a 35K temperature lift.

5.2 Component 2: RHeX-Pozzi

The heat recovery process is one of the critical phases within of the overall Low UP project, in order to extract the maximum possible heat flow with the best efficiency. Concerning the HP-LowUP system, this heat recovery has to be produced from complicated and dirty effluents, with a large amount of suspended particles, significant viscosity, aggressive chemical properties with the equipment ... etc. These circumstances entail the full redesign of the original heat recovery system. The new design has been adapted to the case studies of real industrial processes described in deliverable 3.1, leading to a rotating heat exchanger solution able to meet the following objectives:

- Ability of the heat exchanger to handle contaminated liquids;
- Reduction (if not elimination) of all maintenance costs ;
- The equipment has to be adapted to the characteristics, properties and temperature levels of both cold and hot circulating streams

Figure 55: the standard RCR Pozzi Heat Exchanger

Pozzi Leopoldo S.r.l. has designed and built a self-cleaning heat exchange unit, which has become the most successful model of its kind over the last decades (Figure 55). RCR is an ever-green, patented, sustainable technology with several application fields, such as food processing (juices, meat and poultry, almonds, tomatoes, grains, dairy etc.), tank cleaning, PET recycling, breweries, pharmaceutical processing, pulp and paper, sewage for biological sumps, petroleum/chemical processing/refining...etc.

The original RCR heat exchanger model accomplishes two things: on one hand, all mechanical pollutants are kept under suspension thanks to the stirring rotation action; on the other hand, all thermal surfaces remain clean, increasing the thermodynamic efficiency of the exchanger for the boundary layers are reduced. Little or no maintenance is needed due to lack of the so-called 'fouling' problem, thanks to the rotation system that creates the necessary turbulence which enhances the heat transfer and prevents the build-up of deposits from the dirty effluent

As a summary, the main features of this RCR unit are the following:

- The unit is completely self-cleaning.
- There are no tubes ever to be cleaned, filters or pre-filters required.
- Pozzi devices are modular systems, which makes them ideal for small spaces.

- It does not affect the existing process.
- Quickly and relatively easy installation with a limited amount of piping involved.
- No holding tanks or diverter valves are necessary for continuous processes.

As mentioned in the previous paragraph, a specially adapted device has been designed, in order to carry on with the requirements of the HP-Low UP solution, called RHeX. This new device reaches the following goals:

- Increase the exposed surface area of the exchanger without increasing its weight and overall dimensions.
- Produce a new lenticular shape with a higher internal pressure resistance (clean circuit) and a superior rigidity to obtain a sturdier, fatigue resistant structure.
- Create a more compact, smaller surface/footprint exchanger.
- Counteract the external (dirty circuit) pressure loss with the use of a different shape of dimples.

The design of the heat exchanger accomplishes two things: on one hand, all mechanical pollutants are kept under suspension thanks to the stirring rotation action, while on the other hand all thermal surfaces remain clean, increasing the thermodynamic efficiency of the exchanger. Further description of the heat exchanger can be found on deliverable 3.2.

This new equipment consists of a built self-cleaning heat exchanger unit with two main elements. An open stainless steel, through which the dirty effluent flows by gravity and a series of exchanging shells mounted onto a long hollow shaft (rotor of the heat exchanger). The heat exchange is made by flowing water inside the rotor assembly, which is rotated by a small electric motor. The following figure depicts a 3D model of the heat exchanger, which was used during its design simulations.

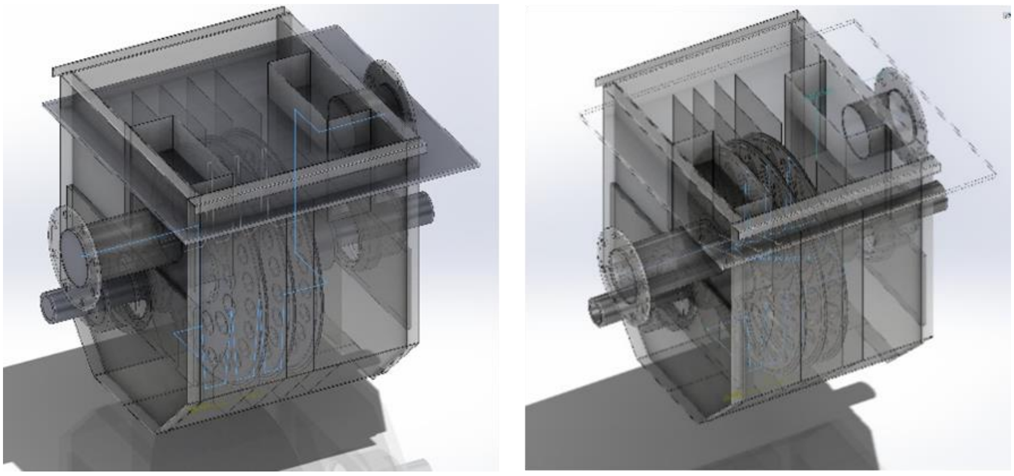


Figure 56. 3D depiction of the heat exchanger's models

The new design evolves previous RCR design incorporating a greater heat exchange surface, both on the rotor part and on the rotating lenticular discs, which results in better and faster heat exchange. In addition, the pressure drop is reduced thanks to the new shape of the dimples pressed on the surface of the lenticular discs, which generate less pressure loss in the circuit, even with very thick or viscous fluids.

Through extensive prototype testing and research, Pozzi also developed a reliable software simulation tool to calculate the expected performance of the heat exchanger based on real production data input. This allows to quantify the expected savings both energy and money wise.

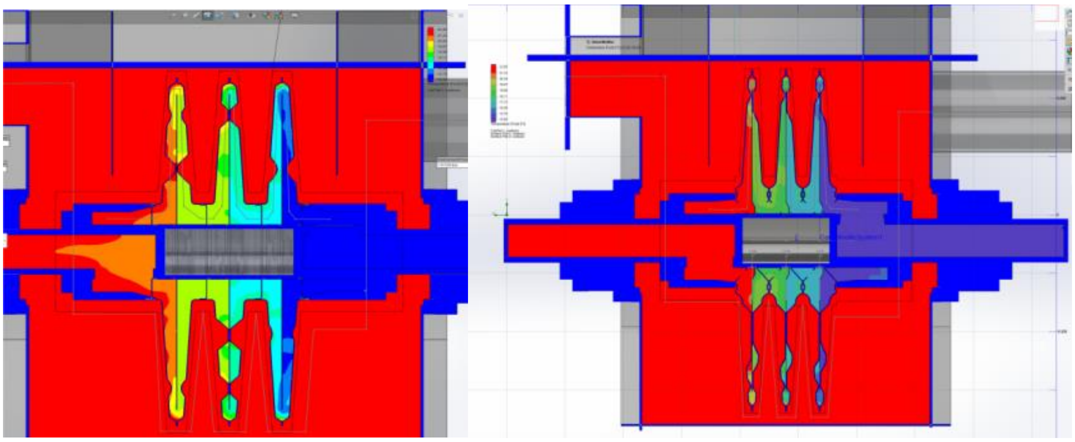


Figure 57. Thermography of internal fluids from right to left in a RCR (left) and a RHeX (right).

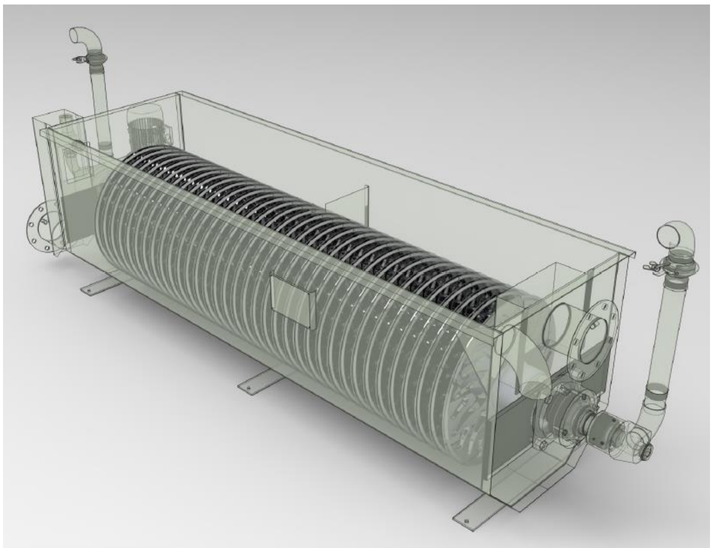


Figure 58. Design of the RHeX

Following the development realized during previous WPs and, according to results achieved during manufacturing, installation, commissioning and operation, a sensible conclusion about the readiness of the prototype systems and components will be carried out at process level, in order to prove the industrial potential and its integration within the energy system. In this regard, the following methodology gives an advice about the main actions carried out and their actual development:

5.2.1 Sensor selection and physical emplacement

Firstly, deliverable 3.4, section 5.3 distinguishes between sensors and actuators, defining them, explaining their purpose and their grade of implementation and development within the overall HP-Low UP system.

Previously of the RHeX design, as Pozzi explains in deliverable D3.2, a test rig for a RCR equipment was installed. The purpose was creating a mathematical model to be used as a base to work with. The data was collected via twelve (12) PT100 temperature probes, four pressure probes and two (2) electromagnetic flow-meters. All these data, along with values obtained from the exchanger motor inverter (for rotor rotational speeds) are collected by a 20-channel analogue data Logger.

In addition, Annex 1 of deliverable D3.4, Table 4 presents a list of control variables of RHeX-Pozzi heat exchanger, including information about the type of signal, measurement range and description for each variable.

Finally, in deliverable D4.5, section 4.1.4 some information about the real elements that integrate the instrumentation and control system of the heat recovery device within the HP- LowUP system is explained, namely:

- Sensors
  - Flowmeter: There has to be installed flow rate sensors for the primary and secondary circuits
  - Temperature meters: There has to be installed temperature sensors at the inlet and outlet for both primary and secondary circuits
  - Outdoor air temperature: in order to record and control the HRS operation, outdoor temperature must be registered.
- Actuators
  - Water pump inverter. To set the flow rate of the secondary circuit, an electrical inverter will control the water pump for the secondary circuit.
  - Sludge pump inverter. For the Setubal plant, it is needed an electrical inverter in order to regulate the sludge pump and set the flow rate into the RHeX.
  - Automatic valve. For the Madrid plant, it is needed to install an automatic valve to regulate the flow rate of sludge into the RHeX.
- Ethernet PLC controller unit

5.2.2 Data acquisition

The content here is the same as in section 3.1.2 of this document, applicable for all HEAT Low-UP, COOL Low-UP and HP Low-UP solutions.

5.2.3 Monitoring and recording of the validation parameters

Done and described in the following sections:

- Deliverable D3.4, section 5.2: At this point, a first approximation about the control and monitoring method of the entire process is made, presenting the monitoring variables that should be measured for each of the technologies involved within the HP-LowUP industrial waste heat recovery & upgrading solution.

  Variables and signals are classified according to their scope and the input/output approach from the local PLCs perspective. Thus, the following categories should be considered:

  - Local inputs: They are low-level input variables for the local PLCs received from sensors.
  - Local outputs: They are low-level output variables for the local PLCs that need to be communicated to actuators in order to make control actions effective.

- Global inputs: They are high-level input variables for the local PLCs received from the Frontend PLC. They will normally correspond to setpoint information and will be communicated through Modbus protocol
- Global outputs: They are output variables for the local PLCs that will be sent to the Frontend PLC. Normally they will correspond to signals that transfer data registered by the sensors, but translated to Modbus protocol.

The figure below shows a very simple sketch of this approach:

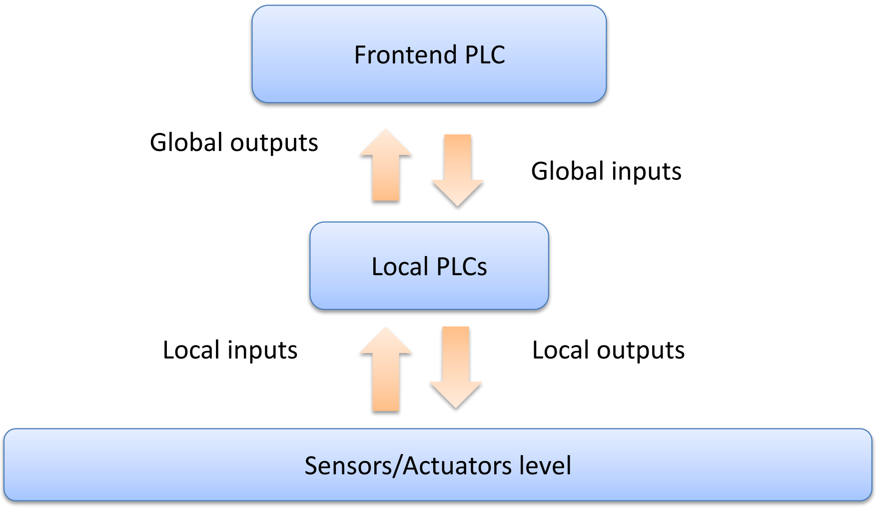


Figure 59: Classification and basic schema of control and monitoring variables

- Deliverable D3.4, section 4.4: refers to the LowUp manager, which will communicate all software modules developed in the project and will orchestrate their communication as well as the communication with external software modules like the SCADA, any external database, and the embedded PC's of the external demo sites.
- Deliverable D3.4, Annex 1: The monitoring variables that should be measured for each of the technologies involved within the HP-LowUP industrial waste heat recovery & upgrading solution are here listed. They allow defining the theoretical main specifications and requirements for the measuring devices to be used in LowUP implementation within WP4. Concerning the RHeX heat exchanger, the Table 19 below (extracted from Annex 1, Table 4) shows all control variables (Local inputs and outputs) for this device.

Table 19: Control variable list for heat recovery HX system from Pozzi

Name	Unit	Signal	Range min.	Range max.	Description and remarks
LOCAL OUTPUTS					
Sludge Pump speed	%	Analog (V)			velocity of the pump or Modulating Valve (sludge side) (Optional)
Sludge Pump On/Off		Digital (V)			pump switching On/Off (sludge side) (Optional)
Water Pump speed	%	Analog (V)			velocity of the pump (water side) (Optional)
Pump On/Off		Digital (V)			pump switching On/Off (water side)
rotor speed	%	Analog (V)			velocity of the HX rotor
rotor on/off		Digital (V)			HX rotor switching On/Off

Dry Cooler Fan speed	%	Analog (V)			velocity of Dry Cooler Fan
Dry Cooler Fan On/Off		Digital (V)			Dry Cooler fan On/Off
HX - Alam	%	Digital (V)			Alarm from the HX - Propietary PLC
LOCAL INPUTS					
Sludge inlet temperature	°C	Analog (mA)	0	50	Sludge inlet temperature at HX
Sludge outlet temperature	°C	Analog (mA)	0	50	Sludge outlet temperature at HX
Sludge volumetric flow	m^3/h	Analog (mA)	0	5	Sludge volumetric flow rate
Water inlet temperature	°C	Analog (mA)	0	50	Water inlet temperature at HX
Water outlet temperature	°C	Analog (mA)	0	50	Water outlet temperature at HX
Water volumetric flow	m^3/h	Analog (mA)	0	5	Water volumetric flow rate
Air Temperature	°C	Analog (mA)	0	50	Dry Cooler Inlet Air Temperature
water inlet pressure	bar	Analog (mA)	0	3	Water inlet temperature at HX
water outlet pressure	bar	Analog (mA)	0	3	Water outlet temperature at HX
HX Alarm INPUT		Digital	0	50	Alarm signals from external device
GLOBAL OUTPUTS					
Sludge Pump speed	%	WORD TCP/IP			velocity of the pump or Modulating Valve (sludge side) (Optional)
Sludge Pump On/Off		WORD TCP/IP			pump switching On/Off (sludge side) (Optional)
Water Pump speed	%	WORD TCP/IP			velocity of the pump (water side) (Optional)
Water Pump On/Off		WORD TCP/IP			pump switching On/Off for the water system
rotor speed	%	WORD TCP/IP			velocity of the HX rotor
rotor on/off		WORD TCP/IP			HX rotor switching On/Off
Dry Cooler Fan speed	%	WORD TCP/IP			velocity of Dry Cooler Fan
Dry Cooler Fan On/Off		WORD TCP/IP			Dry Cooler fan On/Off
HX – Alam Status		WORD TCP/IP			Internal/External Alarm Status of HS
Sludge inlet temperature	°C	WORD TCP/IP			Sludge inlet temperature at HX
Sludge outlet temperature	°C	WORD TCP/IP			Sludge outlet temperature at HX
Sludge volumetric flow	m^3/h	WORD TCP/IP			Sludge water volumetric flow rate
Water inlet temperature	°C	WORD TCP/IP			inlet temperature at HX
Water outlet temperature	°C	WORD TCP/IP			outlet temperature at HX
Water volumetric flow	m^3/h	WORD TCP/IP			water volumetric flow rate
Air Temperature	°C	WORD TCP/IP			Dry Cooler Inlet Air Temperature
water inlet pressure	bar	WORD TCP/IP			Water inlet temperature at HX
water outlet pressure	bar	WORD TCP/IP			Water outlet temperature at HX
HX fouling sensor	-	WORD TCP/IP			Sensor to detect the level of fouling on the HX
GLOBAL INPUTS					
Sludge volume flow setpoint	m^3/h	Discrete TCP/IP			Sludge volumetric flow rate (Optional)

Water volume flow setpoint	m^3/h	Discrete TCP/IP			Water volumetric flow rate (Optional)
Rotor Speed	%	Discrete TCP/IP			velocity of the HX rotor
Dry Cooler Fan speed	%	Discrete TCP/IP			velocity of Dry Cooler Fan
HX - On/Off		Discrete TCP/IP			switching on/off of the system

5.2.4 KPI monitoring

Initially, the Key Performance Indicators are the main parameters considered useful to assess the development of the RCR rotary heat exchanger to the RHeX through the LowUp project. The three KPI parameters observed for this device are for the first time mentioned in deliverable 3.2, section 1.2 and shown below:

Table 20. KPIs for the RHeX heat exchanger

	KPI	Formula	Unit	Goal
1	Surface efficiency gains for each single disk	$\left(\frac{\text{useful surface of the pressed disc}}{\text{raw surface of the unpressed disc}} - 1\right) \times 100$	%	▪ Actual value = 6.79 % ▪ Ultimate goal = 11.30 %
2	Useful surface gain for each rotor meter	$\left(\frac{\text{useful surface of 1 m of the future rotor}}{\text{surface of each meter length of current rotor}} - 1\right) \times 100$	%	▪ Ultimate goal = 30 %
3	Pressure head loss	$\left(\frac{\text{head loss of 1 m future rotor length}}{\text{head loss of each meter length of current rotor}} - 1\right) \times 100$	$\frac{mm\ H_2O}{m\ of\ rotor}$	▪ Ultimate goal = 10.5 %

Based on the improvement of KPIs, a redesign of the RCR model was developed, which is illustrated in the following Table 21, which can be found in deliverable 3.2, section 2.1, Table 1.

Table 21: Result values of KPI 1 and 2.

Model	Surface Area [m^2]	KPI(1) [%]	Number of Discs per meter	Exchangin area per meter lenght	KPI 2 [%]
RAW plate	0,265	N/A	N/A	N/A	N/A
old RCR design	0,283	6,79245283	13,89	7,86	0,0
first RhEx Design	0,299	12,83018868	20,00	10,76	36,93
RhEx H50	0,295	11,32075472	20,00	10,62	35,10
RhEx H58	0,295	11,32075472	17,24	10,17	29,40

In the first new design attempt Instead of circular dimples, a more complex shape was devised. This approach increases the exchanging surface. The previous Table 21 displays the surface area of both designs, showing that the first approach for RHeX had an improvement of about 6% from the RCR's, and Figure 60 and Figure 61 gives a picture of this improvement:

Figure 60: Original RCR lenticular disc design.

Figure 61: First design attempt for RHeX lenticular disc.

In order to increase heat transfer and the overall efficiency of the system, the following measures were carried out:

- The new tear drop shape transfers more rotational velocity to the outer fluid, as well as tightening the average hydraulic diameter of the disc (where the inner fluid flows). This new design will increase the turbulence of both fluids and, therefore, the heat transfer, since the heat transfer coefficient of a fluid is directly linked with the associated Reynold's Number
- The thickness of the faces in this first new design was lowered from 1,5 mm to 1,2 mm, because a lower wall thickness facilitates calorific transfer while decreases the natural heat losses produced in forced convection.
- The inner baffle's thickness was lowered as well from 1 mm to 0,5 mm, leading some slight advantages related to weight and power efficiency, and new possibilities related to welding and assembly.

Beyond the initial design and manufacturing phase, deliverable D3.4, section 5.1: continues analysing more Key Performance Indicators (KPIs), in order to evaluate the equipment in the operation phase in the network and identify what should be measured and for what purpose. The following Table 22, extracted from deliverable 3.4 is a previous step, in which the different subsystems and their objectives are listed. Concerning the heat pump, the goals are clearly defined:

Table 22: Expected impacts for the RHeX heat exchanger of the HP-LowUP industrial solution

System	Objective

Waste water heat recovery system	▪ Self-cleaning fouling free heat exchanger. ▪ Increase heat exchanger efficiency over 70%

Therefore, the KPIs for the RHeX device are later defined in Table 23, which is extracted as well from Table 3 in deliverable D3.4.

Table 23: Definition of Key Performance Indicators (KPIs) for the RHeX heat exchanger of the HP-LowUP industrial solution

	KPIs			Parameters for calculation		
System	Symbol	Unit	Description	Symbol	Unit	Description
Heat Exchanger (HX)	PQ_{HXW}	kW	Instantaneous thermal power availability from the wastewater source (E)	-	-	Direct measurement from energy meter
	EQ_{HXW}	KWh	Total thermal energy availability from the wastewater source (E)	-	-	Direct measurement from energy meter
	PQ_{HXR}	kW	Instantaneous thermal power recovered by the HX (E)	-	-	Direct measurement from energy meter
	EQ_{HXR}	kWh	Total thermal energy power recovered by the HX (E)	-	-	Direct measurement from energy meter
	η_{HR}	-	Heat exchanger efficiency (E)	EQ_{HXR}	kWh	Total thermal energy recovered by the heat exchanger (secondary stream)
				EQ_{HXW}	KWh	Total thermal energy availability from the wastewater source (primary stream)
	ε_{HR}	-	Heat exchanger effectiveness (E)	T_{HXC1}	°C or K	Inlet temperature of the cold fluid (secondary stream)
				T_{HXC2}	°C or K	Outlet temperature of the cold fluid (secondary stream)
				T_{HXH1}	°C or K	Inlet temperature of the hot fluid (primary stream)
				T_{HXH2}	°C or K	Outlet temperature of the hot fluid (primary stream)
				$\dot{m}_{HXww}$	kg/s	Mass flow of wastewater (primary stream)
				$\dot{m}_{HXw}$	kg/s	Mass flow of the water stream (secondary stream)
				c_{HXww}	J/K.kg	Specific heat capacity of the wastewater stream (primary stream)
				c_{HXw}	J/K.kg	Specific heat capacity of the secondary water stream

5.2.5 Results validation of the prototype system installed in a real emplacement

El deliverable D3.2, section 3 describes a validation rig, which has been used to test both the RCR and the RHeX to their maximum potentials, in order to establish a base-point of data and build mathematical models. This is the better approximation that we can have, related to a validation of the device installed in a real emplacement.

Next, along sections 3.1, 3.5 and 3.6, is detailed the dynamic behaviour of the prototype RHeX heat exchanger taking into account the previous KPIs. This is an initial validation carried out in Pozzi's own factory, using the experimentation rig mentioned above. The three behaviours evaluated are the following:

- Rotational behaviour:

  With reference to KPIs it is important to prove that the new shape, ideally conceived to "facilitate the flow of fluid" towards the outlet of the exchanger, effectively does so, in such a way to counteract the pressure losses generated by the reduction of clearance, satisfying KPI 2. The first test of the new setup was performed by rotating the exchanger at various speeds into a static bath in order to establish the pressure head generated by the effect of the new shape when rotation is exerted.

  The results showed follow the expected results of the finite-elements simulations, fully proving the engineering hypothesis at the basis of the new design. Therefore, the new shape of the RHeX technology facilitates the flow of fluid, matching the objective referred in KPI 2.

  This result is extremely important in order to allow the RHeX exchanger to be used with very viscous fluids (paints, for example) where the original characteristic of gravity flowing on the dirty side of the exchanger was hindered by the pressure loss generated by viscosity when the fluid, at high flow rate, was passing through the exchanger on the dirty side (that is to say, the outside of the rotor).

- Thermal behaviour: Several tests were carried out, imitating the study cases where the equipment will be installed.

  - Pulp & paper mill:

    The necessary flow has to achieve a 30 kW thermal power exchanged, considering a ΔT of 5K in the clean water side and a waste water inlet temperature of 40°C. In this case, the most important test was carried out under the following conditions:

    - The primary circuit flow (dirty side) is regulated at 30 l/m and enters the heat exchanger at 40°C
    - The secondary circuit flow (clean side) was regulated at 85 l/m entering the exchanger at 20°C

    Under these conditions, this RHeX prototype is able to offer the required yield, exchanging more than 30 kW and complying with the established requirements.

  - Water treatment plant:

    The necessary flow has to achieve a 30 kW thermal power exchanged, considering a ΔT of 5K in the clean water side and a waste water inlet temperature of 35°C. In this case, the most important test was carried out under the following conditions:

    - The primary circuit flow (dirty side) is regulated at 50 l/m and enters the heat exchanger at 35°C

- The secondary circuit flow (clean side) was regulated at 85 l/m entering the exchanger at 20°C

  Under these conditions, this RHeX prototype, with only 8 discs mounted, is able to exchange 33 kW, obtaining an overall efficiency of 66% and complying with the established requirements.

- Insulation behaviour:

  Two tests were run in order to determine the influence of an external insulation liner onto the main body of the exchanger. Keeping basically the same input situation in terms of temperature and flow rate, a first test run has been performed without any insulation. Afterwards, a 2nd test was performed, applying a 35 mm-thick lining of self-adhesive, closed cell, polyurethane foam with reflective Mylar external surface. The ambient temperature has been measured at 19,5°C.

  The results show how a simple insulation on the outer walls of the trough is reducing about 2% of the heat losses towards the environment.

It is possible to say that the dynamic and thermal behaviour of the new RHeX exchanger was correctly tested. All the experimental data collected seem to confirm the results of the achieved simulation modelling of the design stage. Therefore, the following statements about the final product are definitely established:

- It is a better heat exchanger, able to extract energy from very polluted streams of low-enthalpy effluents without the burden of extensive cleaning maintenance, coping with the LowUP goals
- It is a unit with better robustness, able to withstand higher pressures: the bursting pressure of the new disks increased from 24 bars to the current 36 bars allowing an increase of the nominal RHeX pressure 3 to 5 bars, which means a significant 55% improvement
- The device is able to effectively help the movement of thick and viscous fluids thanks to the added innovative pumping function achieved by the new design, which takes advantage of the dynamic characteristics of the opposing slopes of the teardrop shapes impressed on the disc surfaces. Hence the pressure loss decreases on the primary circuit (the dirty side)
- The RHeX heat exchanger leaves behind the fully-welded structure of the RCR rotor, providing a disc-level modularity instead of a fixed-length one. Therefore, it will be finally possible to customize the exchanger surface areas and replace any lenticular disc for maintenance purposes

The fulfilment of the predetermined KPIs make the peculiar characteristics of RHeX the winning choice towards circular economy strategies by means of a no-fail, constantly efficient, sustainable energy recovery system.

Beyond the post-manufacturing tests carried out at the Pozzi´s factory, the testing of the newly designed exchanger has been done in 2 different sites:

- Industrial papermill sewage heat recovery in Setubal (Portugal)
- Civil WTP heat recovery from digestor sludge in Madrid (Spain)

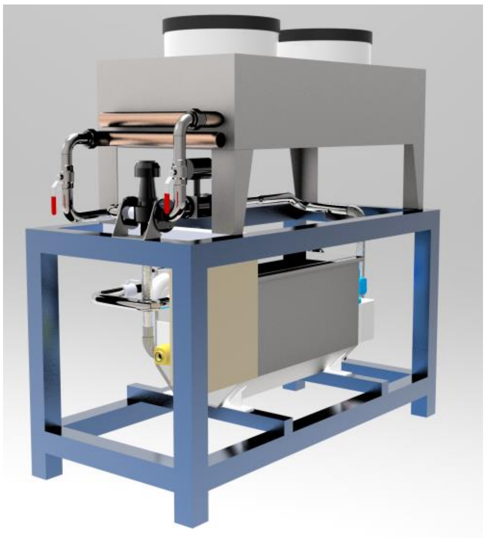


Figure 62: Heat exchanger prototype for the HP-LowUP solution

The assembly (Figure 62), consisting of a RHeX-16T heat exchanger at the bottom of the skid and a dry cooler on top, simulates the conditions of heat recovery and heat dissipation that can be achieved by combining the heat exchanger to a heat pump.

The hardware and software embedded into the control system has given the opportunity to continuously monitor the following variables:

- Water outlet temperature
- Water pump speed
- Water inlet pressure
- Water outlet pressure
- Water volumetric flow
- Water total volume
- Water heat flow
- Water total heat
- Sludge inlet temperature
- Sludge outlet temperature
- Sludge pump speed
- Sludge volumetric flow
- Sludge total volume
- Sludge heat flow
- Sludge total heat
- Air temperature
- Dry cooler fan speed
- Time run

As a final conclusion, the new design will have no match on the market when treating difficult streams. These achievements are under the innovation and upgrade of the pre-existing RCR model.

5.2.6 Next steps to reach next TRL

In the framework of the LowUP project, Pozzi was able to design, develop and test the prototype in their dedicated lab first and then in the demo sites of Madrid and Setúbal. In parallel, they also finalized the RHeX heat exchanger as a stand-alone product, beginning its market commercialization in 2019. Since then, about 80 units have been installed in different application fields, thus totally completing the TRL assessment.

Out of the extensive field experience accumulated with these installations, a design review of few components of the unit has been taking place.

- End caps: the original design of the rotor end caps was adequate for the small size rotor units delivered within the LowUP real emplacement framework, but proved to become critically weak for more important rotor lengths.

  A radical re-design of the part has been put in place substituting the welded assembly with a cast stainless-steel part with satisfactory results both in performance and cost-efficiency.

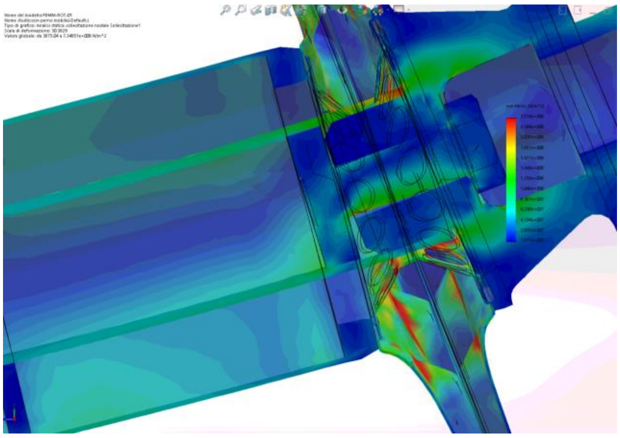


Figure 63: **FEMM stress analysis of the newly designed end-caps**

The new design has by now become a standard component equipping all produced rotors.

- Weir meter: as a further improvement on the through design, a rather crude but effective flow meter has been added to the design. The use of this device is double:
  - By lifting the weir blade insert, the overall level in the tank will rise; this is useful when a large unit is used with a rather low flow-rate, thus allowing a better coverage of the rotor disks by the primary fluid.
  - Furthermore, the weir blade insert has a series of marks on its right side: these marks give an indication of the primary fluid flow-rate as one reads the plume level passing over the weir blade in the slot.

Figure 64: The weir & level device

The reading is obviously intended only as an indication and is not a precise measurement, but can be very useful during the set-up of the exchanger.

Basically, the flow-rate is proportional to the plume height (h) read on the weir scale. A rough estimate of the flow-rate can be read from the following graph:

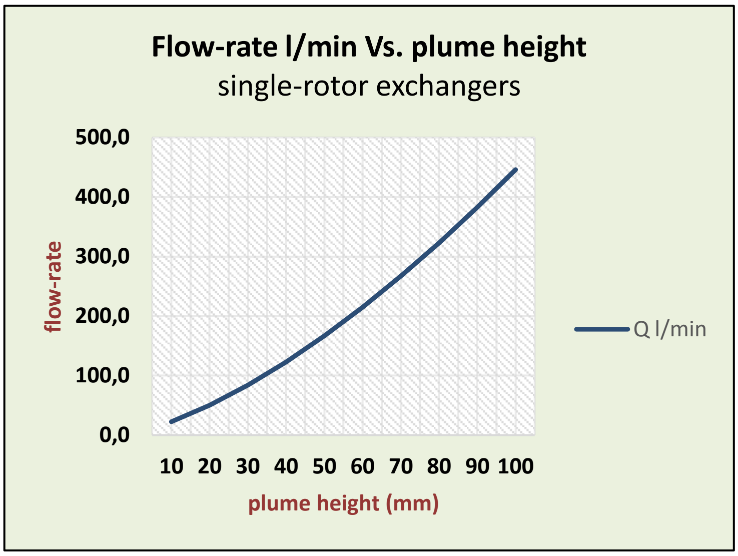


Figure 65: Flow-rate measure (single rotor)

5.3 Component 3: LowUp Optimizer (D3.5)

The present component consists of a detailed explanation of the mathematical models made for each of the three technologies that constitute the HP-LowUP solution. Each point include their correspondent equations system and simulated results. Additionally, a description of the characterization process of the developed technologies is made, presenting the applied validation scenarios and the obtained results.

Based on the experimental results, an adjustment of the theoretical models has been performed in order to reduce any performance gaps between the mathematical model and the equipment's operation.

The LowUP optimizer was developed for the following systems:

- Waste heat recovery system model (RHeX-Pozzi Heat Exchanger)

  This section presents the mathematical model, experimental results and model validation that was obtained by the operation of the heat exchanger under real operating conditions in the pulp and paper factory company Navigator in Setubal, Portugal.

Figure 66. Depiction of the heat exchanger unit and its operation scheme (red: primary circuit, blue: secondary circuit)

  The installed system is composed by four main devices. The heat exchanger unit (subject of validation), a dry cooler equipment to emulate different energy demand conditions, as well as a water pump and a sludge pump for the circulation of the effluents of the primary and secondary circuits of the HX. The following figure depicts the installed equipment, which was mounted in a single skid for its easier integration and management.

- Heat pump system model (GEA Heat pump)

  Concerning the heat pump equipment, the experimental analysis and HIL characterization was carried out in the thermal laboratory of Tecnalia, located in Guipuzkoa (Spain). The main objective of the developed equipment is to boost efficiently the low thermal level of the wasted source into useful heat for the industrial process. The following figure presents a schematic drawing of its internal structure and elements.

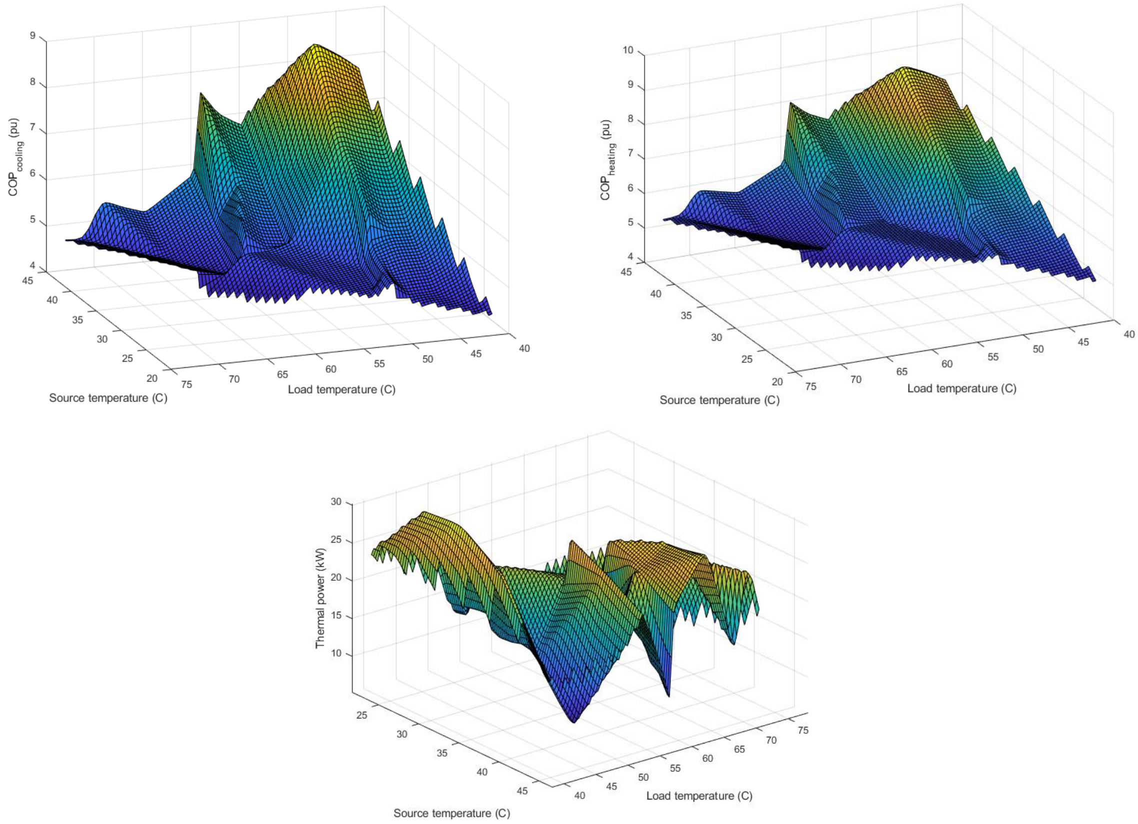


Figure 67. Representation of the thermal power curve of the HP in relation to source and load temperatures.

GEA has designed this unit based on data from the simulated operation conditions of the project´s demo sites. The units are in accordance with EN-standards and the requirements under the Pressure Equipment Directive 2014/68/EU. For more information, a detailed description of the developed Heat Pump is provided in deliverable D3.3 “High temperature cost effective heat pump”.

- Control algorithm for the optimal operation of the HP-LowUP system (no physical installation)

  A control algorithm for the HP-LowUP system was developed, in order to determine the optimal operation based on its source and load temperature conditions. The control strategy is focused on the regulation of the equipment´s operation, with the aim of satisfy the set point temperature of the heat pump´s load, while minimizing the overall energy consumption of the system.
  The optimization algorithm is based on the interior-point method, which is considered as one of the most efficient methods to solve linear optimization problems. This method presents polynomial complexity and, in practice, is a highly efficient from a computational point of view.

5.3.1 Sensor selection and physical emplacement

Firstly, deliverable 3.4, section 5.3 distinguishes between sensors and actuators, defining them, explaining their purpose and their grade of implementation and development within the overall HP-Low UP system.

As before, there are 3 systems considered. Concerning the heat recovery system, and, in particular, the Pozzi RHeX heat exchanger, instrumentation devices and sensors are specified in deliverable 3.2, where the following elements are distinguished:

- Temperature probes PT100, 12 units
- Pressure probes, 4 units
- Electromagnetic Flow-meters, 2 units
- Heat exchanger´s motor inverter (for rotor rotational speeds)
- All these data, along with values obtained from the exchanger motor inverter (for rotor rotational speeds) are collected by a 20-channel analogue Data Logger. Provision is made to be able to log an extra ten digital data for status information.

For the Heat Pump installation, Deliverable 3.5, section 2.2.3, in the context of the experimental validation, mentions which kind of sensors were installed, in order to gather information about working temperatures, volume flows, energy consumptions and thermal power in different internal circuits and components of the heat pump.

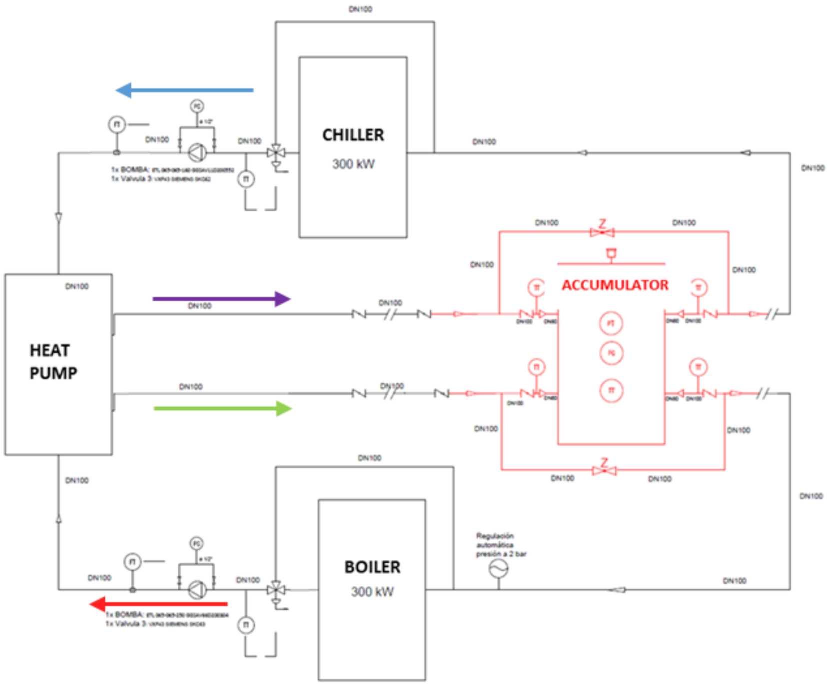


Figure 68. Diagram of the heat pump system, including instrumentation and control

Referring to the control system, this one concerns to the entire HP-LowUP system, hence, sensors and instruments here are the same as in the previous points

5.3.2 Data acquisition

The content here is the same as in section 3.1.2 of this document, applicable for all HEAT Low-UP, COOL Low-UP and HP Low-UP solutions.

5.3.3 Monitoring and recording of the validation parameters

This task is done and described, for the entire HP-Low UP solution, in the following sections:

- Deliverable 3.4, section 5.2: At this point, a first approximation about the control and monitoring method of the entire process is made, presenting the monitoring variables that should be measured for each of the technologies involved within the HP-LowUP industrial waste heat recovery & upgrading solution.

Variables and signals are classified according to their scope and the input/output approach from the local PLCs perspective. Thus, the following categories should be considered:

- Local inputs: They are low-level input variables for the local PLCs received from sensors.
- Local outputs: They are low-level output variables for the local PLCs that need to be communicated to actuators in order to make control actions effective.
- Global inputs: They are high-level input variables for the local PLCs received from the Frontend PLC. They will normally correspond to setpoint information and will be communicated through Modbus protocol
- Global outputs: They are output variables for the local PLCs that will be sent to the Frontend PLC. Normally they will correspond to signals that transfer data registered by the sensors, but translated to Modbus protocol.

The figure below shows a very simple sketch of this approach:

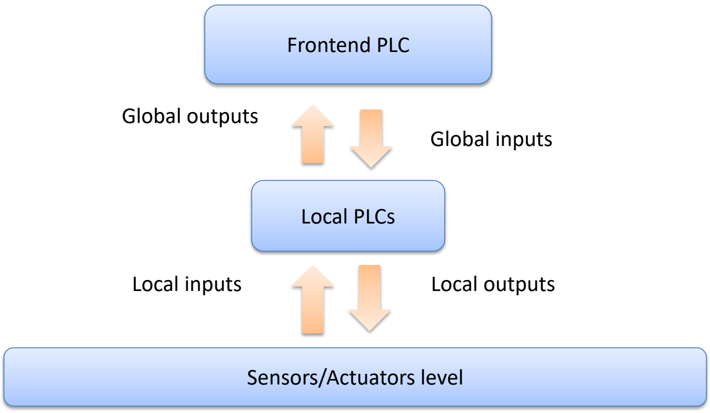


Figure 69: Classification and basic schema of control and monitoring variables

- Deliverable 3.4, section 4.4: refers to the LowUp manager, which will communicate all software modules developed in the project and will orchestrate their communication as well as the communication with external software modules like the SCADA, any external database, and the embedded PC's of the external demo sites.
- Deliverable 4.5, section 4.2.3: talks about the heat pump's control system installed at the real demo site emplacements (Madrid, Setúbal and Gipuzkoa), detailing the following parts:
  - The Omni system: this is the own control system of the heat pump. There, the setpoints desired for each experiment will be introduced. The system is able to monitor and register all the variables needed for the characterisation, and allows some advanced control features, such as fix the working power load fraction
  - Laboratory setup: centralised control system called "Delphin", where all the operating variables are monitored in the SCADA platform, which allows the remote operation of the equipment.

5.3.4 KPI monitoring

About the heat exchanger, a testing plan for the characterization of the RHeX at Madrid and Setúbal facilities has been developed, including different heat loads and operating in order to test the installation. The following table shows the variables to be studied, and the selected operation levels for each variable:

Table 24. Description of variables to be tested (D4.11, section 3.1)

	Variable	Description
Controllable	**F**: Frequency of the rotor [Hz]	Rotating speed of the rotor of the RHeX. Modifies the thermal transmissivity UA of the heat exchanger. This variable is controlled with the frequency inverter of the motor that drives the rotor. This value will remain steady at **50 Hz**.
	SVF: Sludge volume flow	The flow rate of the sludge containing the waste heat. It flows through the primary circuit. Controlled either with the flow valve or with the frequency inverter of the sludge pump.
	WVF: Water volume flow	The flow rate of water from the RHeX to the dry cooler. It flows through the secondary circuit. Controlled with the frequency inverter of the water pump.
	DTW: Waterside temperature difference	The temperature difference at the secondary circuit (water side) has to be kept at the constant value DT = 5 K, to reproduce the requested operating conditions of the HP evaporator circuit. This condition can be achieved with the HRS control system of the dry cooler's fan, though it
Uncontrollable	**AIT**: Air inlet temperature	The temperature of the air entering into the dry cooler, in other words, outdoor air temperature. This magnitude is expressed as a range since it can take values within a continuous domain. It cannot be controlled, but the working values are estimated from 12°C to 47°C (see D4.5).
	SIT: Sludge inlet temperature	The temperature of the sludge exiting the biodigester and entering the RHeX. It cannot be predicted, though is estimated from 30°C to 50°C.

Based on the characteristics of both plants in Madrid and Setúbal (see deliverable 4.5). The considered values for these variables are collected in the following table:

Table 25. Sets of values for the test variables (D4.11, section 3.1)

Value level	F [Hz]	SVF [l/h]	WVF [l/h]	SIT range [°C]	Mean SIT [°C]	DTW [°C]
1	50Hz	3000	4800	30-35	32.5	5
2		5000	7200	35.1-40	37.5	
3				40.1-45	42.5	
4				45.1-50	47.5	

In addition, for the performance analysis of the equipment installed in the Navigator Plant, the following variables, were acquired with a 2 minutes interval:

- Water Inlet Temperature (ºC)
- Water Outlet Temperature (ºC)
- Water Pump Speed (%)
- Volumetric Flow of water (m^3/h)

- Total Volume of water (m^3)
- Heat Flow of water (MCal/h)
- Total Heat (MCal)
- Sludge Inlet Temperature (ºC)
- Sludge Outlet Temperature (ºC)
- Sludge Pump Speed (%)
- Volumetric Flow of sludge (m^3/h)
- Total Volume of sludge (m^3)
- Total Heat Flow of sludge (MCal/h)
- Total Heat of sludge (MCal)
- Rotor Speed (%)
- Air Temperature (K)
- Sludge Inlet Level (mm)
- Sludge Outlet Level (mm)

Subsequently, Figure 70 is obtained, presenting an 8 days graphs of registered dataset, depicting the inlet temperatures of both the primary and secondary circuits (sludge and water, respectively), their flow rates, as well as the estimated energy savings. In this case, these are the variables that can be considered as the KPI parameters.

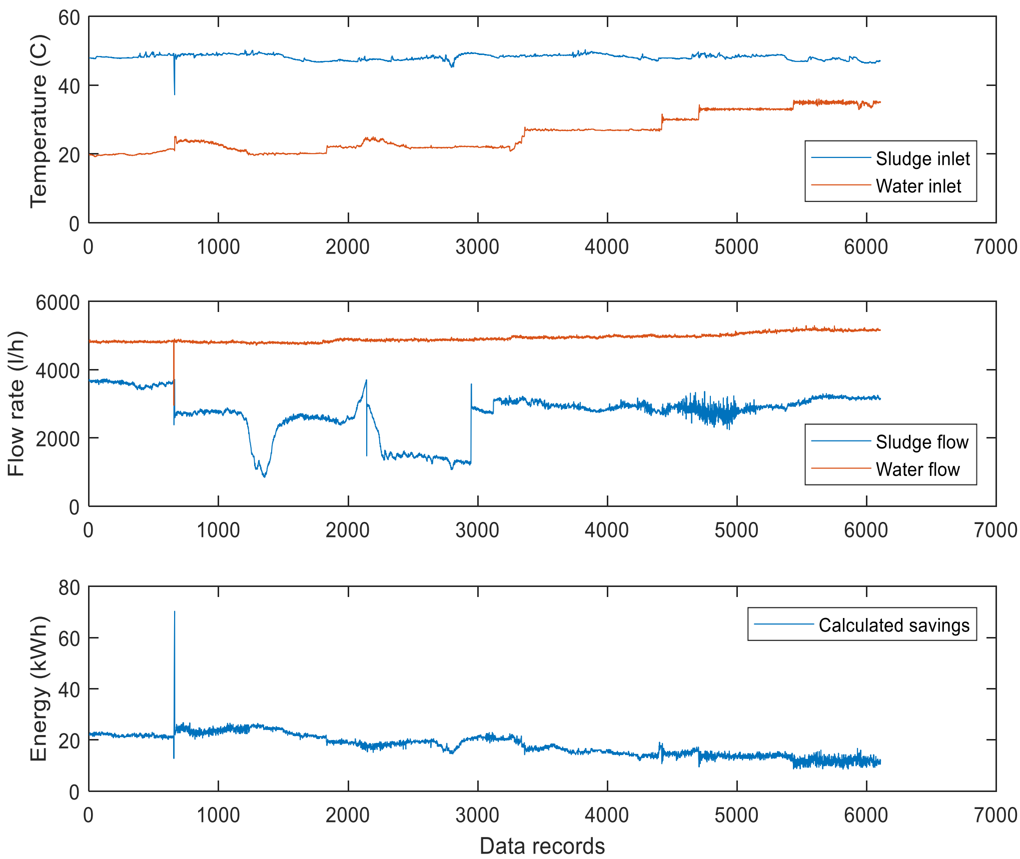


Figure 70. Example of data measurements for the of the characterization of the heat exchanger.

On the other hand, concerning about the heat pump, in deliverable 4.11, section 4 a complete characterization for this device is described, explaining in detail which variables have been studied, and summarized in the following table:

Table 26. Description of variables to be tested (Heat Pump)

Variable	Description
Tout condenser (°C)	HP outlet setpoint temperature
ΔT Lift (°C)	Difference between Tout at the condenser and Tout at the evaporator.
Tin evaporator (°C)	Temperature to be supplied at the inlet of the evaporator (through the gas boiler in Tecnalia lab)
Q load (%)	Load ratio of the HP. It has to be achieved by the chiller. The maximum load to be achieved by the HP is a DT=10K at the condenser side.
ΔT (°C)	The thermal difference at the condenser. Related to the load ratio.
Tin condenser (°C)	Inlet temperature at the condenser, to be supplied by the chiller
Flow evap	Water flow at the evaporator. Fixed by the specs of the equipment. It corresponds to DT=5K.
Flow cond	Water flow at the condenser. It corresponds to ΔT (°C) desired to test.
Control strategy	The control system of the HP can operate in two modes: PI and FLOW.

The constraints of the heat pump system were the following:

- ΔT Lift < 35°C: The temperature lift T_condenser_out (setpoint) – T_evaporator_out cannot exceed 35°C, otherwise overpressure issues are possible.
- ΔT Lift > 20°C: Likewise, if it drops below 20°C, a low-pressure issue is possible
- The maximum evaporator inlet temperature cannot exceed 45°C.

Next, deliverable 3.5, section 2.2.3 refers to several real data sets attached to the operational behaviour of the heat pump working in the LowUP Optimizer, including characterization tests, with the aim of analyse the equipment performance under several load set points, temperatures and flows. In principle, the results of these tests are used to generate the three-axis performance curves that represent the real heating & cooling efficiency and thermal power of the heat pump device in relation to source and load temperatures.

Both data sets (tests and performance curves, Deliverable 3.5, Figures 13, 14 and 15) obtained from experimental work, are used to replace the previous performance curves of the model, obtained from manufacturer´s specifications, and validate the models described below, in section 5.3.5.

The third component of the Low UP Optimizer concerns the control system, which purpose, as mentioned before, is focused on the regulation of the equipment´s operation trying to satisfy the set point temperature of the heat pump´s load, while minimizing the overall energy consumption of the system.

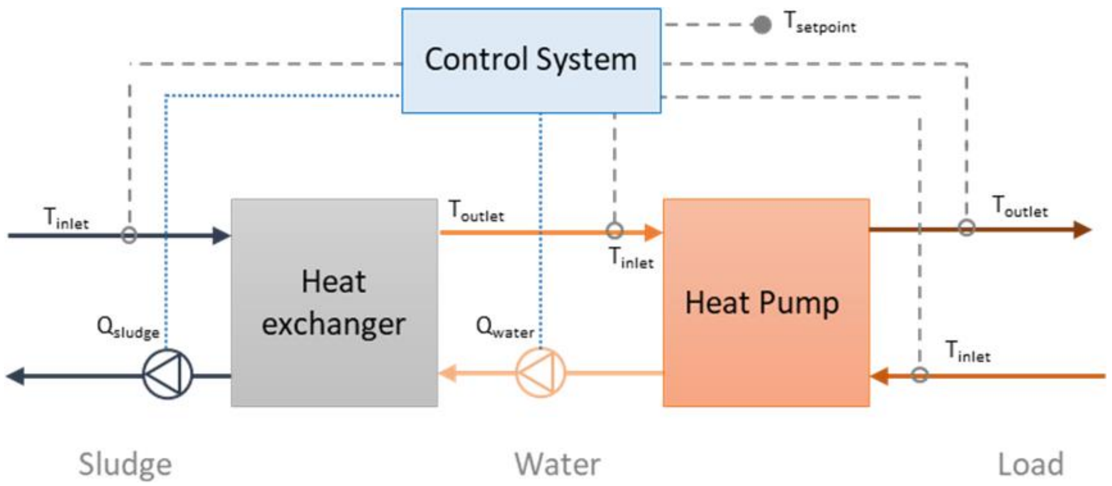


Figure 71. Block diagram of the control system of the HP-LowUP.

After analysing the optimization algorithm, summarized in Figure 71, the main KPIs of the system are the following:

- COP surface of the heat pump based on the operating conditions
- Thermal power performance of the heat pump based on the operating conditions (kW)
- Coefficient of performance of the heat pump in heating mode
- Total energy consumption (kW)

5.3.5 Results validation of the prototype system installed in a real emplacement

The mathematical model of the equipment has been developed in a function format, consisting of five inputs and two output variables. This structure allows its easy integration and use in simulation environments as well as its combination and evaluation with models of other technologies. The following figure depicts the inputs-outputs structure of the model.

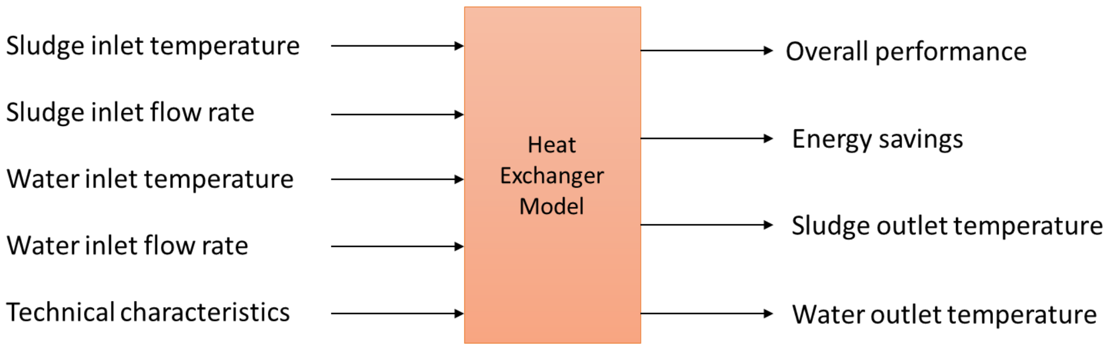


Figure 72. Block diagram with the inputs/outputs structure of the heat exchanger's model.

On the other side, once the experimental data from the heat exchanger was obtained, it was used to validate the calculations of the mathematical model by applying the same operating conditions. A comparison of the sludge and water outlet temperatures showed a performance gap between the model and the actual operation of the equipment. This happened due to the internal coefficients of the mathematical expressions, which were set empirically by means of laboratory validations during its construction. To correct the deviation, the model was recalibrated, producing the following validation results:

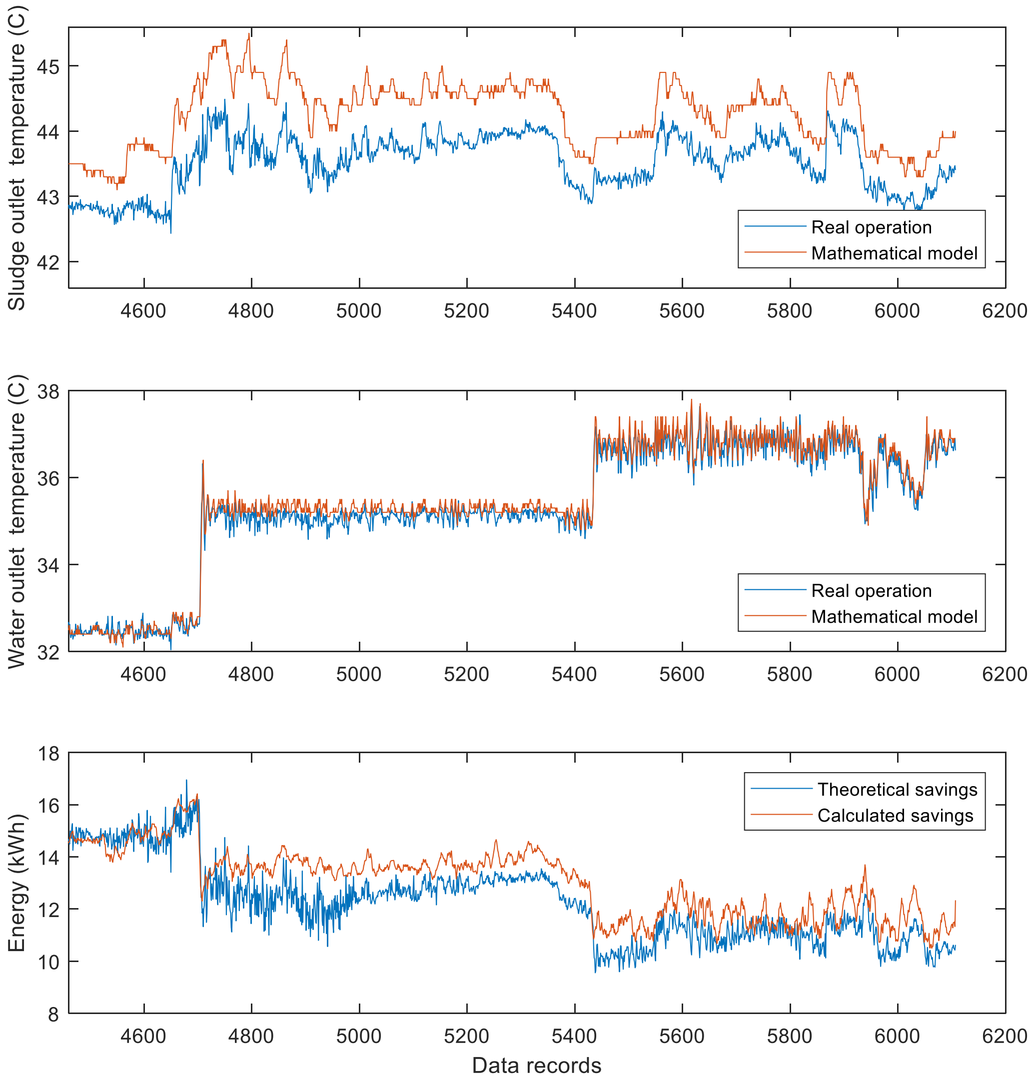


Figure 73. Comparison between the results of the adjusted model and the real performance of the heat exchanger

From here, Table 27, which indicates the fitting results of the models in terms of the RMSE, is obtained:

Table 27. Fitting results of the model's performance after the adjustment.

Description	RMSE result	
	Per Unit	%
Outlet temperature of sludge	1,499 ºC	3,3
Outlet temperature of water	0,625 ºC	1,65
Energy savings	3,63 kWh	5,17

Looking at the data, the error is less than 3.5% and 1.7% in the outlet temperatures of water and sludge, respectively, which represents a good approximation of less than 1.5 and 1°C difference between the calculated value and the actual real experimental measurement. Regarding the energy savings, the error is somewhat higher, more than 5%, which represents an average of 3.63 kWh deviation and means that the model is more optimistic than reality in this aspect. As conclusion, it is possible to say that, although the model is realistic and quite reliable, a readjustment and/or recalibration would be appropriate, in order to refine the results regarding the energy savings.

Concerning the heat pump, a simulation model for the GEA equipment was developed in Matlab platform, (Figure 74) including the following tasks:

- COP calculation depending on the design conditions, like cold/hot sink water temperatures (deliverable 3.3, section 2.3 and deliverable 3.5, section 2.2)
- Transient simulations for a given time are performed obtaining several results, including figures where power capacity and COP are calculated for different evaporator and condenser temperatures (deliverable 3.3, section 3.1 and deliverable 3.5, section 2.2).
- Simulations of operation examples, using the developed mathematical model to replicate the operating conditions of the WWTP (Biodigester). The results describe temporal profiles of the source and load side temperatures and heat transfer rates between the heat pump and the biodigester, describing the overall behaviour of the entire system (deliverable 3.3, section 3.1).

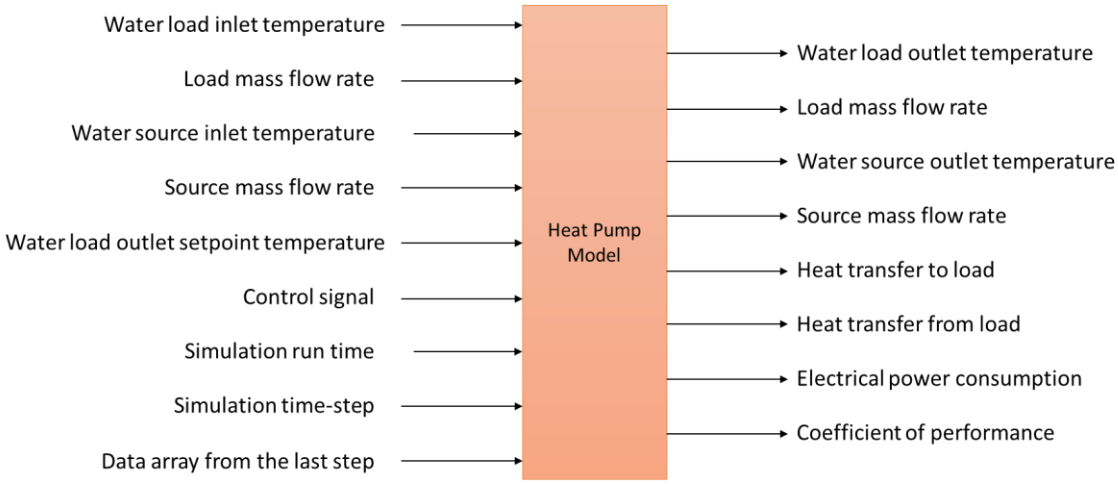


Figure 74: Block diagram with the inputs/outputs structure of the heat pump model.

With the adjusted HP performance maps update, the mathematical model is run for the same input as the experimental cases. Figure 75 and Figure 76 present the results of the thermal power, as well as the coefficient of performance of the heat pump in both heating and cooling modes (deliverable 3.5, section 2.2.3):

Figure 75 shows how the adjustment between both variables (Q_{load} and Q_{source}) is almost perfect for the first two graphs, with almost no error. For the third graph (electrical power), the situation is slightly different, because the calculated value and the actual real electrical power value moves between 1 and 3 kW. This could happen because of the internal inefficiencies and irreversibility of the heat pump, which in reality, during the real operation, tend to be greater than during the manufacturing process. This discrepancy is maybe the cause that explains why a small error is further observed in Figure 76. Even taking these observations into account, the model is very accurate and highly realistic, in reference to the actual operation of the process.

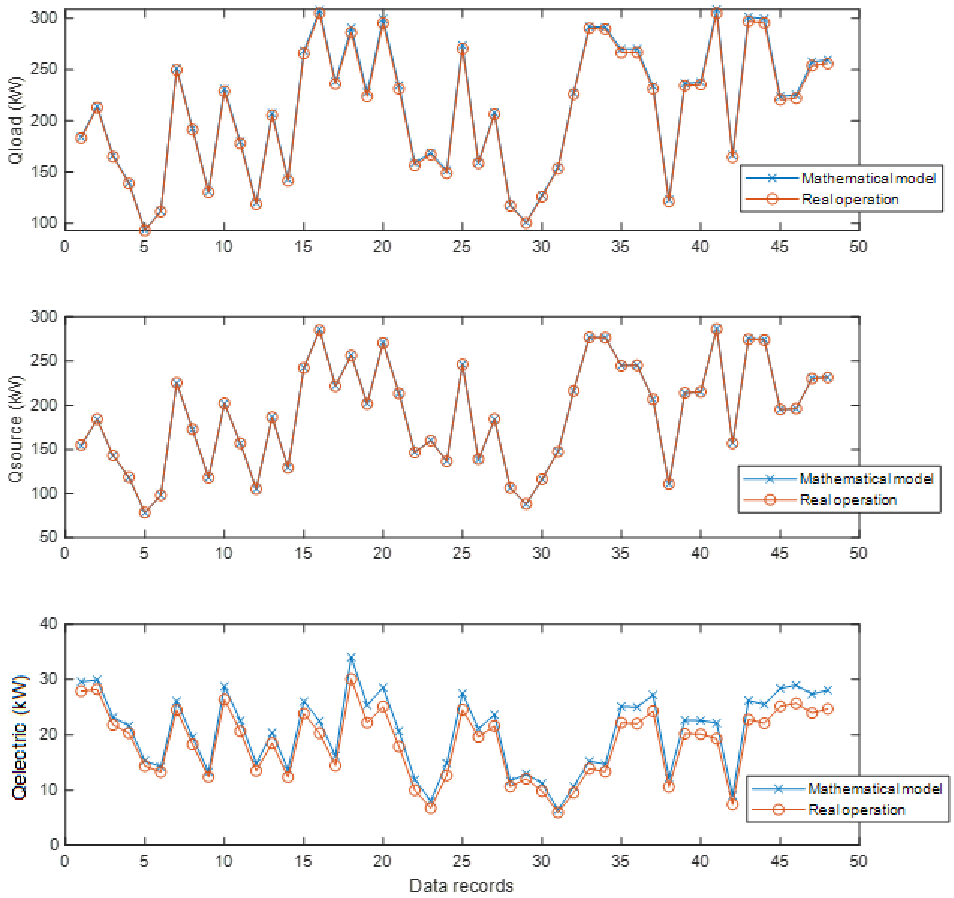


Figure 75. Load and source heat capacity and electrical power of the heat pump characterization.

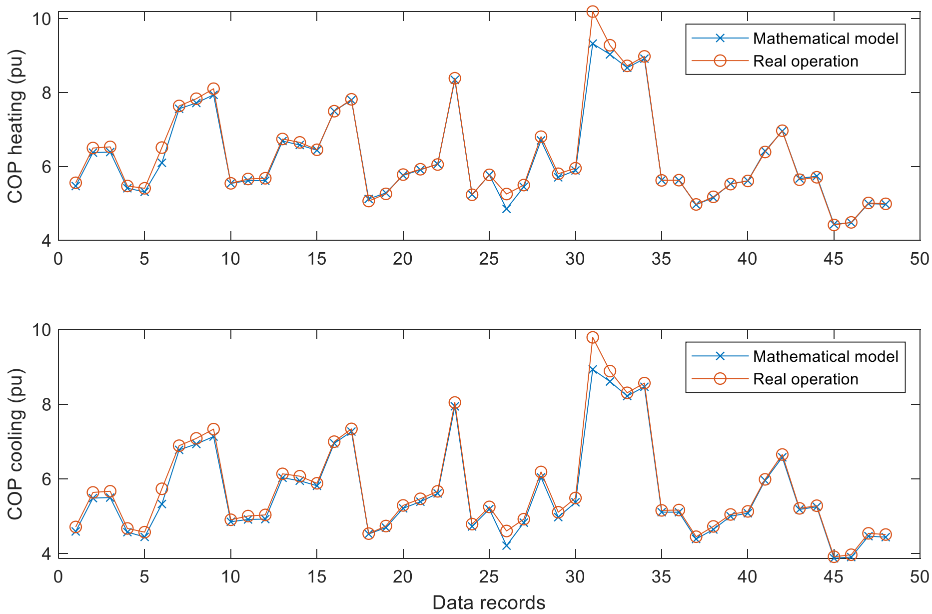


Figure 76. Example of performance ratio data measurements of the heat pump characterization.

5.3.6 Next steps to reach next TRL

In order to reach a TRL 8 of an actual system with commercial qualification, there are several actions to be carried out:

- Develop a communications interface. The communications with the sensors and actuators has been developed manually for the LowUp systems, as well as its link with the LowUp Manager. For commercial applications an User Interface should be developed that allows a quick configuration following the market standards of SCADA systems.
- Improve optimization algorithms. The optimization of very complex systems as the ones in that project, can result in non-convergent situations for the algorithm. In that case the system can get stuck. To avoid that, besides of creating additional conditions that break the stuck situations, the algorithm must be improved with more robust routines that can handle complex situations and discriminate either the local minimum has been found or to find other path toward the optimal.

5.4 Component 4: Supervisory Control Operation and Surveillance (D3.6)

The anomaly detection models implemented for both systems (RHeX and HP) were expected to be data driven and developed base on ML techniques. However, some problems in the data acquisition systems together with delays in the installation of them and the limited useful data given the final approach was mixed between ML techniques and other techniques like moving floating windows and adaptable thresholds.

The anomaly detection (also outlier detection) is a technique used to identify rare items, events or observations which raise suspicions by differing significantly from most of the data. They could be also called outliers, novelties, noise, deviations, and exceptions, and typically these anomalous items will translate to some kind of problem such structural defect, malfunctions, drifts, broken parts of a system, etc.

The anomalies can be classified in three groups:

- Punctual anomalies: a single data instance is anomalous if it is too away from the rest. Corresponds to the filtering module.
- Contextual anomalies: the anomaly is context specific. This type of anomaly is common in time series data.

Anomaly detection is similar, but not quite the same, as noise removal or novelty detection:

- Novelty detection refers to the identification of an unobserved pattern in new observations not included in the training data.
- Noise removal is the process of removing noise from a significant signal.

To solve this problem, a block has been implemented that allows, in a dynamic way, the creation of different models based on AI algorithms, where the user can specify which parameters or variables are used for the training of said models and, therefore, for perform anomaly detection. From here, it is necessary to i) study each of the anomalies to analyse how to identify them (by creating new variables if necessary) with respect to the normal behaviour of the rest of the data and ii) create a model capable of carrying out this detection to which data will be provided periodically to carry out this process. Many of the AI algorithms perform this task as a batch process, but in this case it is necessary to be able to do it in real time, so it is necessary use algorithms or techniques that generate a model that can be used to validate new values.

5.4.1 Sensor selection and physical emplacement

The supervisory System has been installed in the Seville Demo site for the smart operation of the Cool-LowUP and Heat-LowUP solutions. In addition data form its tests and operation until the end of the project has been analysed for surveillance purposes in order to improve its future management.

On the other side HP-LowUP solution has not been operated together due to their systems has not been installed in the same sites, and the emulated operation expected in the proposal was disabled by the EC. However, the performance tests for the HP and the tests done for the Heat exchanger have generated data that has been used to develop anomaly detection models.

5.4.2 Data acquisition of the different characteristic parameters

For the Seville demo site data is acquired by the SCADA solution and stored in a MySQL database. For the heat exchanger form Pozzi all data generated in the two demo sites deployed has been stored locally by an industrial PC and synchronized with a 3G mobile connection to the central Database in Seville. For the HP the data has been collect by its own control.

5.4.3 Monitoring and recording of the validation parameters

The validation of the supervisory control has been done manually based on forced situation in the SCADA and manual executions of the LowUP Manager to run the operational rules of the solutions. In addition, test periods wave defined when the supervisory system lead by the LowUP-Manager, was executed hourly to evaluate the control rules based on daily optimized configurations and occupation and weather forecasts for the next day. More details on that can be found in D4.14.

The validation of the surveillance developments, regarding the three solutions of the project, have been done using the data available, that in all cases have been less than expected in the proposal and required for these type of developments. When possible, for the WP3 systems, this lack of data has been solved using the main part for the data for models training, and the other, for testing. On the other side, the developments for WP2 systems, need to be further worked. The data available for the operation of all systems includes almost all 2020 but including limited days of real operation of the systems. Only restricted (due to the systems are connected between them and not in a test frame) operational tests are available for the systems performance evaluation. Joint and real operation of the systems is needed in real condition for the improvement and development of anomaly detection models. However, the alarms from systems and defined by plant operators that have been raised during 2020, have been studied describing hypothetical situations of risk and generating some recommendations for the plant operators and for the manufacturers. Finally, the validation of this section would conclude when normal operation of the systems involved for a long period (1 season) was available.

5.4.4 KPI monitoring

No KPI monitoring has been done

5.4.5 Validation conclusions of the prototype system installed in a real emplacement

The Supervisory control of the COOL-LowUP and Heat-LowUP solutions has been used evaluated during the last 6 months of the project with great results, some bugs and improvement have been implemented to allow a better traceability of the ongoing situation but according to plant operators the system is working as expected and it can run autonomously. Validations results can be obtained in D4.14.

The surveillance models has not been installed and have been implemented on batch with real data extracted from project databases.

5.4.6 Next steps to reach next TRL level

Further work is needed to assure that the Supervisory system is able to be used in a commercial installation. More data is needed from operation on real environments for that, at least one season. This would allow to better measure the impact of this supervisory system compared with a normal operation. Regarding the surveillance part the situation is the same.

As recommendations for the next TRL, the supervisory system should have a dedicated user interface to interact with, and to show all parameter used in their internal rules.

6 Conclusions

The application of all the systems for the three LowUp solutions (1: Heat-LowUp, 2: Cool-LowUp and 3: HP-LowUp) has been carried out. The systems have been installed and operated for months, and all of the have proved to be suitable for their design purposes, while it is true that some of them have found operational issues during the execution of the project that difficulted their operation in design conditions.

Some of the systems have achieved higher TRL levels with the innovation actions carried out and tested during the project, such as the radiant floor from RDZ or the chilled beams from Halton. The reaching of higher TRL has put new challenges to be overcome to reach next level. Others have reached the maximum possible TRL such as the thermal photovoltaic panels (PVT) from Endef which are ready to be launched to the market. On the other hand, the rotating heat exchanger from Pozzi already implemented the innovations from the project and went to the market with the novel systems during the execution of the LowUp project.

The validation of the systems vindicates the relevance of that systems in the frame of the market existing solutions, and their contribution to the circular economy paradigm, and decarbonization of climatization and industrial sectors.