Low valued energy sources UPgrading for buildings and industry uses

LowUP Test Plan for relevant environment 1

Deliverable D4.10

Lead Beneficiary: CARTIF

March/2020

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www.lowup-h2020.eu

The LowUP project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement n°723930.

Document Information

Grant Agreement:	723930
Project Title:	Low valued energy sources UPgrading for buildings and industry uses
Project Acronym:	LowUP
Project Start Date:	November 1st, 2016
Related work package:	WP 4: Installation, operation and validation in a relevant environment
Related task(s):	Task 4.4: Operation and demonstration of overall efficiencies
Lead Organisation:	CARTIF
Submission date:	March 13th, 2020
Dissemination Level:	Public

History

Date	Submitted by	Reviewed by	Version (Notes)
29.10.2019	Francisco .J. Palomo (ACC)	Manuel Andrés (CAR)	v0_Table of contents
21.02.2020	Alberto Belda (CAR)	Carlos Ramos (ACC)	v1_First full draft
09.03.2020	Manuel Andrés (CAR) Alberto Belda (CAR)	Carlos Ramos (ACC)	v2_Revised version - HEATLowUP tests
13.03.2020	Manuel Andrés (CAR) Alberto Belda (CAR)	Rafael C. Socorro (ACC)	V3_Final version of D4.10

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

About LowUP

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Executive Summary

This report (D4.10 "Test plan for relevant environment 1") has been elaborated within the LowUP Project (GA #723930) and provides a plan to execute the activities related to performance testing of HEAT-LowUP and COOL-LowUP solutions within the framework of Task 4.4.

After the proper implementation of LowUP technologies at the project test sites, Task 4.4 will focus on stable and continuous operation of the LowUP systems in the relevant operational environments. As a result, extensive characterization of the individual equipment and the building integrated solutions will be achieved for the calibration of relevant models and the operational performance validation of each involved technology.

In preparation for this stage, this document addresses the identification of objectives for the characterization and monitoring programmes to be conducted, as well as the definition of those suitable tests in order to obtain relevant results and proof of performances.

The activity will be split in four different phases: On site test and Commissioning, Start-up of the whole system, characterization of the LowUP system and the Operation and Validation at system level.

This deliverable (D4.10) aims to bring an execution plan of all these activities, focused in the relevant environment 1, namely Seville demo site.

Keywords

Commissioning, start-up, characterization, operation, validation, action plan

List of acronyms and abbreviations

AHU	Air-Handling Unit
CB	Chilled Beams
COP	Coefficient Of Performance
EAD	External Air Damper
HVAC	Heating, Ventilation, and Air Conditioning
IAD	Impulsion Air Damper
NOCT	Nominal Operating Cell Temperature
OA	Open-Air (free cooling)
O&M	Operation and Maintenance
PCM	Phase-Change Material
PLC	Programmable Logic Controller
PR	Performance Ratio
RAD	Return Air Damper
R&D	Research and Development
STC	Standard Test Conditions
VAV	Variable Air Volume (system)
2WV	Two-Way Valve
3WV	Three-Way Valve

1 Introduction

After the integration of the Cool-LowUP and Heat-LowUP systems in the demo sites of Seville and Badajoz, the next step is to carry out the testing, operation and validation of all the technologies that take part within the LowUP project, as well as the comparison of the results of these analysis with those from previous work packages related to systems simulations, manufacturers testing and expected energy consumptions, cooling and heating productions, energy efficiency and cost savings.

Task 4.4 will focus on stable and continuous operation of the LowUP solutions in the relevant operational environments, which is essential to validate the performance of the system, and identify and correct any malfunction. The functional performance testing will be tackled from a bottom-up approach; i.e. the study search for malfunctions will start by confirming the performance of every elementary component and progressively working up to the whole system. This approach requires significant efforts, but allows a safer identification of local defaults and prepares for reliable performance evaluation. The task will be split in four different phases, with different purposes, as shown in Figure 1:

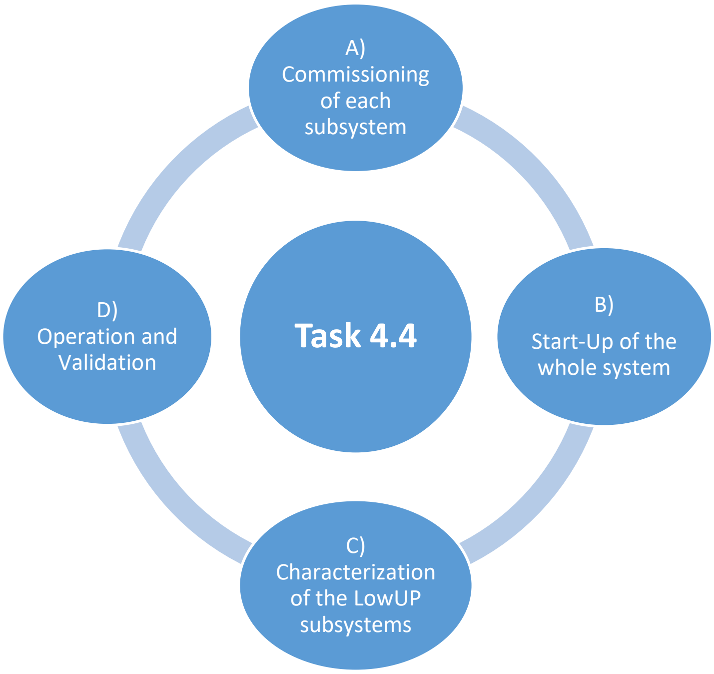


Figure 1: Task 4.4 - scheme of content

The activities within the task 4.4 are explained in detail below:

A) On-site test and Commissioning: each component, after being properly installed according to manufacturer indications and specifications, will be re-tested individually to achieve powering, control, safety, operation and design conditions for the operational test site.

B) Start-Up of the whole system: LowUP systems will be firstly run to reach their nominal working conditions, and secondly, will be operated to exceed their limits and to modulate the operational conditions in order to check: potential operational gaps, crashes, programming and dimensioning errors, quality of connections and insulation, fault detection system, degree of automation, operation sequences, transitory states, leakages, vibrations, acoustic limits, accessibility for O&M, reliability and robustness of individual technologies, friendliness of user interface, or communication limits.

C) Characterization of the LowUP system: once the start-up phase is completed, each component would be run within their working limits in order to achieve their actual working curve and verify the results of design and manufacturing, for corrections and improvements. Since these characterization tests will be performed in a real environment where not all the relevant variables can be totally controlled, a second characterization test will be developed based on readings from the operation of the system under normal conditions.

D) Operation and Validation at system level: the system will be operated continuously and automatically during a significant timespan, reproducing different working conditions and adapting to different scenarios in terms of load profiles, maintenance activities, coordination with existing equipment, etc. This period will be recorded in order to be used for the validation of the TRNSYS models, the development of the predictive maintenance strategies, as well as the evaluation of identified KPIs.

All these activities, belonging to Task 4.4, will be developed in subsequent project phases and reported in detail in upcoming deliverables (D4.12 and D4.14). However, the purpose of this deliverable is to establish the basis, in the form of an action plan, which enables to fulfil all the activities mentioned above for the demo sites of Seville and Badajoz in the time and manner established by the Description of the Action. In some of the referred 4 phases, the formal process of the activities will be very similar for both HEAT-LowUP and COOL-LowUP as well as for the involved equipment. Only certain variations depending on the particular specifications will be adapted.

2 Seville demo site

2.1 Cool LowUP System

The Cool LowUP system comprises four main devices: Chiller/AHU, Chilled beams (CB), Cooling Tower and PCM-based storage tank. Below Figure 2 shows a simplified diagram of the facility:

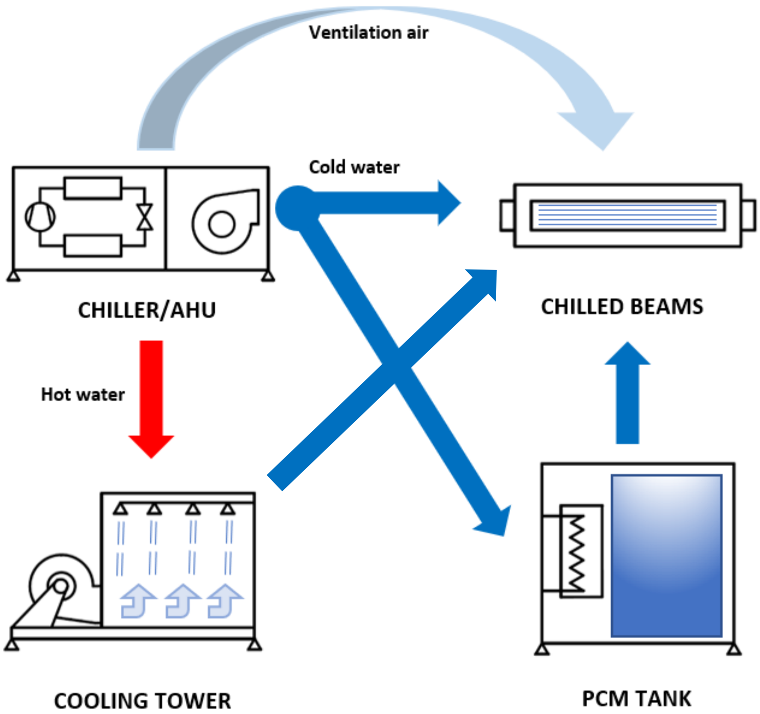


Figure 2: Cool LowUP – concept diagram

The chiller cools the water during the night, and the energy produced is stored in the Phase-Change Material (PCM tank), which provides the CB when it is necessary to deal with the cooling loads of the building. The cooling tower is used to reject the heat from the chiller condenser or to directly supply free cooling water to the CB when favourable ambient conditions are met. In the case that the energy stored in the PCM tank is not enough, the energy is supplied to the CB directly by the chiller. The ventilation air is produced in the AHU, which is integrated with the chiller in the same system.

The following images offer an overview of the systems integration in the plant:

Figure 3: Chiller/AHU integration

Figure 4: PCM storage tank integration

Figure 5: Chilled beams integration

Figure 6: Condensation tower

2.1.1 Commissioning of each system

This section aims to describe the generic steps to be followed by qualified balancing and start-up technicians for the commissioning of each Cool LowUP subsystem. The commissioning process in this project will include the setting up, balancing, adjustment, start-up and testing of each subsystem, to ensure that all the requirements are met as specified by manufacturers. This procedure is set to be completed before operation and validation of the system once all the elements are integrated. Start-up checklists provided by the manufacturers for every equipment will be methodically followed; hence following operations are just a reference to complement specific steps included in official installation and use manuals and the overall detailed commissioning process will be described in D4.12.

For every subsystem, before and after the start-up, next checklist must be completed:

Before start-up of every subsystem:

- Collect design and as-built documents, control schematics, shop drawings and manuals from manufacturers. Check nameplate data of equipment.
- Check that additional devices necessary for the proper development of the commission phase are ready, i.e. available, accurate and calibrated. In case there may be any potential disruption of the normal activity in the location where the commission will take place, ensure the users are perfectly aware and have expressed written conformance with these procedures.
- Verify that all the equipment is installed in the expected locations as specified in as-built documents and in conformity with design requirements, manufacturer's requisites and constructions details: piping, valves, air vents, strainers, flexible connectors, thermometers and gauges, etc.
- The electrical power supply line must be sectioned at the beginning. The sectioning device must be locked. Make sure no tension is present. Verify the unit is connected to the ground plant.
- Check electrical connections and protections, including the proper tightening of the screws that fix the conductors in the board.
- Inspect and remove any accumulated debris in the equipment (e.g. leaves, cardboard, fixed obstacles). Ensure that the plumbing system has been washed and drain the wash before connecting the different subsystems.
- Check the tightness and alignment of drive belts, tightness of mechanical hold-down bolts, oil level in gear reducer drive systems and alignment of couplings.
- Rotate fans by hand and insure that blades clear all points of the fan shroud (ONLY WHEN THE SYSTEM IS UNPLUGGED).
- Check that circulation pumps are not blocked.
- Check lubrication of equipment.
- Check that the system is properly filled with the corresponding fluids at the required conditions: (1) check that water pressure meets requirements from the manufacture specifications and there are no broken lines in the water pipe network, to avoid possible leakages; (2) check the refrigerant charges are correct, and verify the absence of oil stains which might mean leakages; (3) fill the tank with the phase change material (PCM) and check the ice level sensor.
- Compare the control schemes with the final placement of the different sensors, actuators, valves or pumps, and check that positions of valves and dampers are convenient for the start-up of the system. Check the set-points and modify them if necessary.
- Supply power to the system and check the supplied voltage and net frequency values are within the limit of: 230 ±6% single phase system; 400/3/50 ± 6% three-phase system. Control the unbalancing of the phases is lower than 2%.
- Register the initial conditions of the subsystems in the start-up reports, and document pre-operation procedures.

After the start-up of all subsystems:

- Check the communications. A correct display of all the variables on the SCADA system is essential, and the writing variables must be modified remotely.
- Ensure a correct labelling system identifies relevant elements, as well as flow directions, fixed setpoints and warnings or any other relevant information for operation and maintenance activities.
- Document commissioning activities; report the correct operation of every subsystem, as well as any identified malfunction or deficiencies (e.g. abnormal noise, vibration) and their corresponding corrective measures carried out during the commissioning phase.

As previously stated, any additional operations included in commissioning procedures and start-up checklists provided by manufacturers will have preference before previous items.

2.1.1.1 Chiller/AHU

The following image shows a detailed scheme of the Chiller/AHU system:

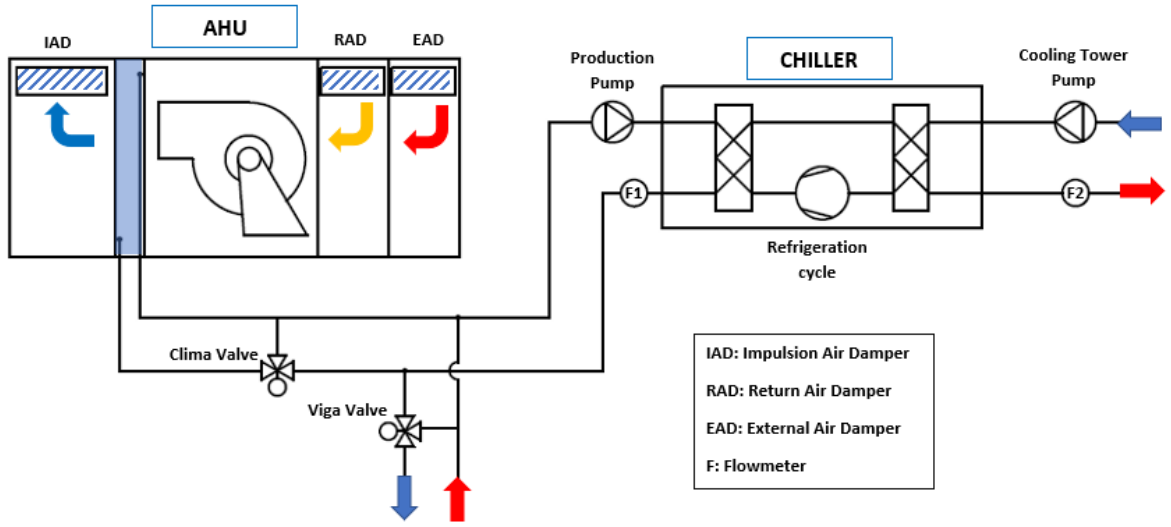


Figure 7: Detailed diagram of the Chiller/AHU system

The commissioning of the chiller/AHU will consist of the following steps during start-up phase:

Subsystems:

- Pumps: Check the rotational direction and the nominal flow. A low flow does not allow that the compressor runs. A low flow could be consequence of the presence of air bubbles inside the water system. In order to remove these bubbles, the system must be vented. Operate pump at minimum and full flow conditions, and verify, by comparing the readings to manufacturer values: inlet/outlet pressures and flowrates of the pump, amperages and voltages of the motor (phase-to-phase and phase-to-ground). Identify unusual or unexpected vibration, noises, etc.
- Compressor: Check the start/stop and the flow.
- Fan: Nominal flow and pressure should be reached.

Sensors:

- Temperature and pressure sensors: these devices should send a specific signal; hence, the correct measurement of the variables is to be verified.
- Flowmeter: Test these devices to detect any possible error in the configuration, flow direction or the presence of air bubbles inside the installation.

Valves:

- Two valves control the process, and according to the operation mode, the position of the valves will be modified. Change the position of the valves manually, in order to check that they operate properly.

Dampers:

- Three dampers comprise the AHU mixing section: supply, return and outdoor air. The air quality probe will control the percentage of opening of the outdoor air damper and is to be checked.

Integrated Chiller/AHU system:

- Through the display test, check different operation modes including start/stop function, and confirm that the system operates properly in every mode.

2.1.1.2 PCM Tank

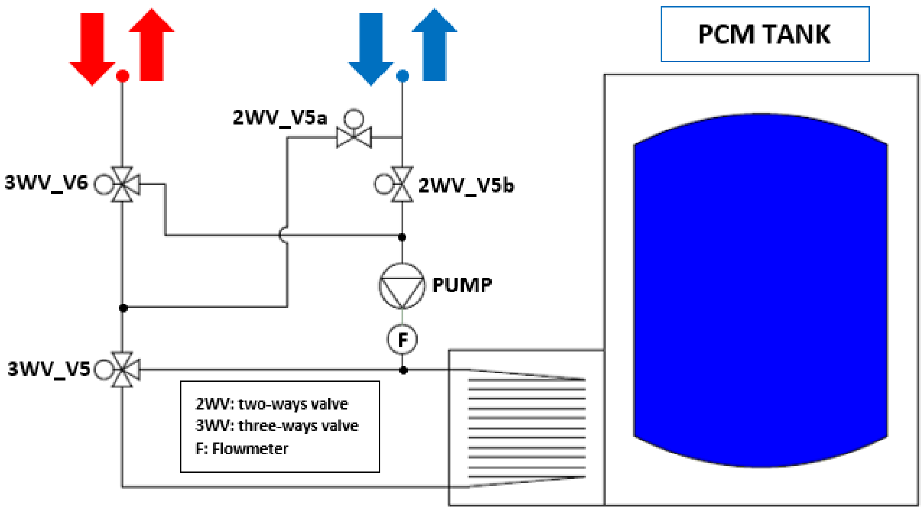


Figure 8: PCM Tank system scheme

The commissioning of this system will consist of:

- Checking the proper operation of the pump: rotational direction and nominal flow.
- Removing the bubbles from the water pipe network.
- Manual configuring the valves to check every operation mode.
- Checking the requirements of the control logic programmed in the PLC for each of the main four modes: stop, charge, discharge and manual. Checking that the configuration of all actuators is the correct in these modes.

Figure 9: Phase change material stored in ACCIONA facilities

2.1.1.3 Chilled Beams

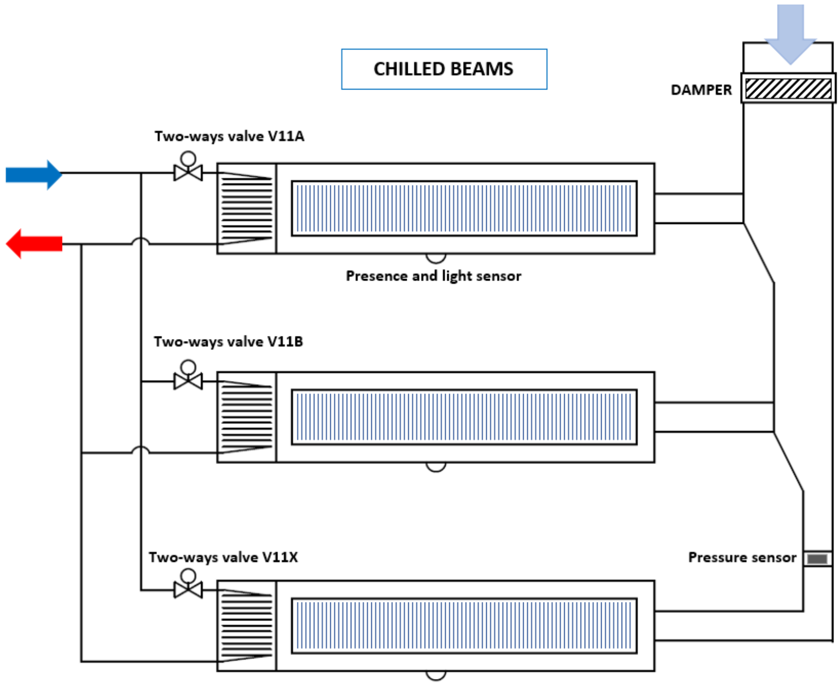


Figure 10: Chilled beams scheme

The most important part of the start-up phase will be to check the communication system in order to have a proper control of the CB in remote mode.

The commissioning of this system will include:

- Removing air bubbles of the installation.
- Checking that the valves perform properly at all expected modes.
- Checking the proper operation of the damper controlling the air flow. Depending on the air quality, this device is opened or closed, managed by the PLC.
- Checking the correct operation of the light which is controlled by the presence and light sensor. Calibrate the sensor.
- Checking the proper response of the system to changes depending on the operating conditions.
- Testing all of the eleven beams included in the system.

2.1.1.4 Cooling Tower

This system was already installed in the Acciona facilities in Seville's site before the start of LowUP, belonging to previous R&D projects. The purpose of this system is to reject heat from the chiller or provide direct free cooling water to the CB under favourable weather conditions. The start-up will mainly consist of checking that all the devices comprising this system work properly.

During the start-up:

- Check that the water-circulating system, the interior filling and the basin of the cooling water are thoroughly cleaned of all direct and foreign matters.
- Check the external pump: direction of rotation, nominal and maximum flows, and associated power.
- Internal pump and fan must work properly in terms of flow rate, power and direction of rotation. Cooling Tower fan(s) do not operate unless associated cooling tower pump(s) are running.
- Check the three-way-valves.
- Balance water flow following the cooling tower manufacturer's procedure.
- Check the function of the control system at all forward speeds.
- Check no excessive vibration in the cooling tower structure.

- Adapt the programming of the PLC of this system in order to integrate with the other system.
- Schedule preventative maintenance to avoid legionella infections.

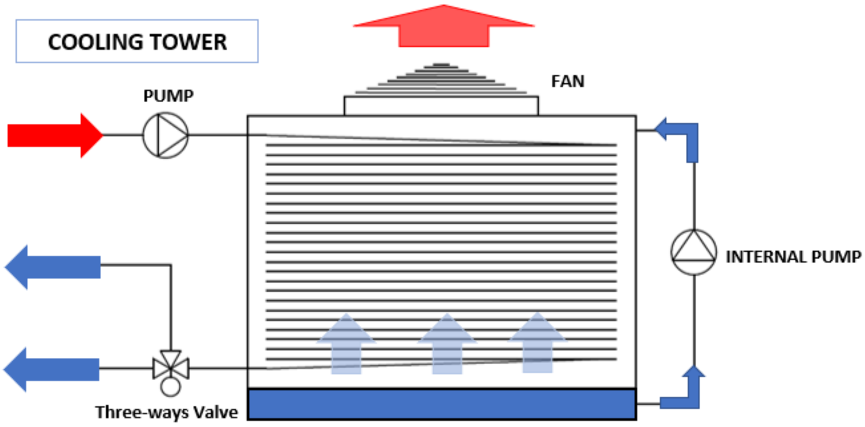


Figure 11: Cooling Tower scheme

2.1.2 Start-up of the global system

Once the commissioning phase is completed for every constituent element individually, the correct performance of the system as a whole per intent of design will be evaluated; i.e. it will be checked that all subsystems are correctly integrated from a functional perspective, including the start-up of the global system, shut down and sequence of operation. The start-up tests of the global system will include: automatic equipment operation, automatic system operation and alarms and safe operation. Results from these activities will be documented. Additionally, the proper triggering of the different operation modes will be tested, as planned in previous phase for every subsystem separately.

First, the system will be operated under design conditions, and after evaluating the correct performance of all the elements (e.g. supplied powers are within acceptable design limits, temperatures follow expected ranges), the system will be secondly forced to exceed design set-points and reach alert limits and action limits (see Figure 12). This process will help checking key performance aspects such as fault detection system, communication limits, operational gaps, programming errors, transitory states or reliability and robustness of the system, among others.

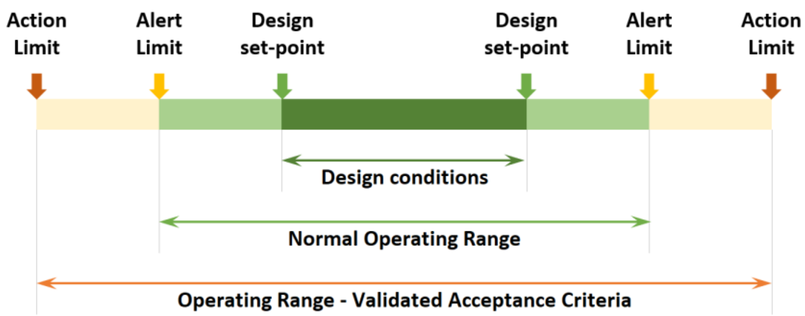


Figure 12: System operating ranges

As described in the previous section, each subsystem (i.e. PCM Tank, Chiller/AHU, Cooling Tower, CB) is conformed by a set of devices (e.g. pumps, valves, fans), and all these devices are controlled by the subsystems' PLCs. A front-end PLC will be the element in charge of sending to the subsystems' PLCs some orders in form of setpoints. This front-end PLC is the "brain" of the global system, and besides controlling the subsystems, is also in charge of sending the orders to the auxiliary devices (e.g. pumps, valves) which do not belong to any subsystem (see image below). **During the start-up of the global system, the proper execution of the control strategy programmed in the front-end PLC will be evaluated.** Thus, start-up activities will be constituted by a sequence of tasks to validate the proper operation of the system under its different operational modes, thanks the controlled modification of relevant variables during a significant timespan.

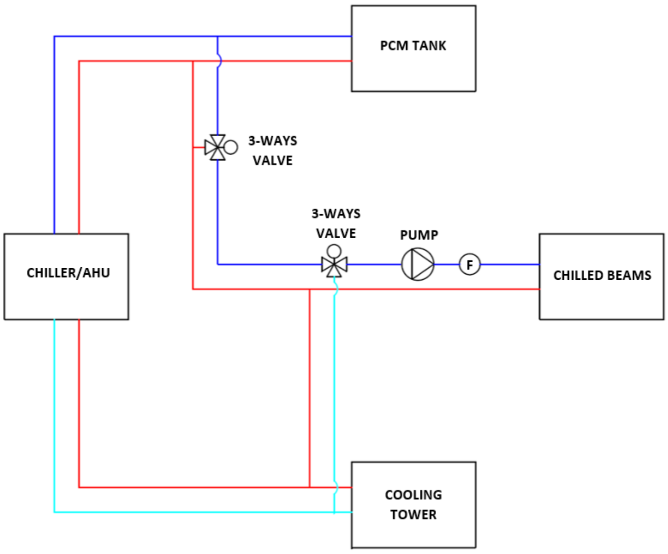


Figure 13: Global system – auxiliary devices

At a very first level (high-level layer), the overall control of the COOL-LowUP solution is ruled by a set of operational modes that are enabled/disabled depending on the occurrence of different boundary conditions. Such modes are described in more detail in D2.10; however this document presents a brief summary of the proposed control strategy, as shown in the diagram below (Figure 14):

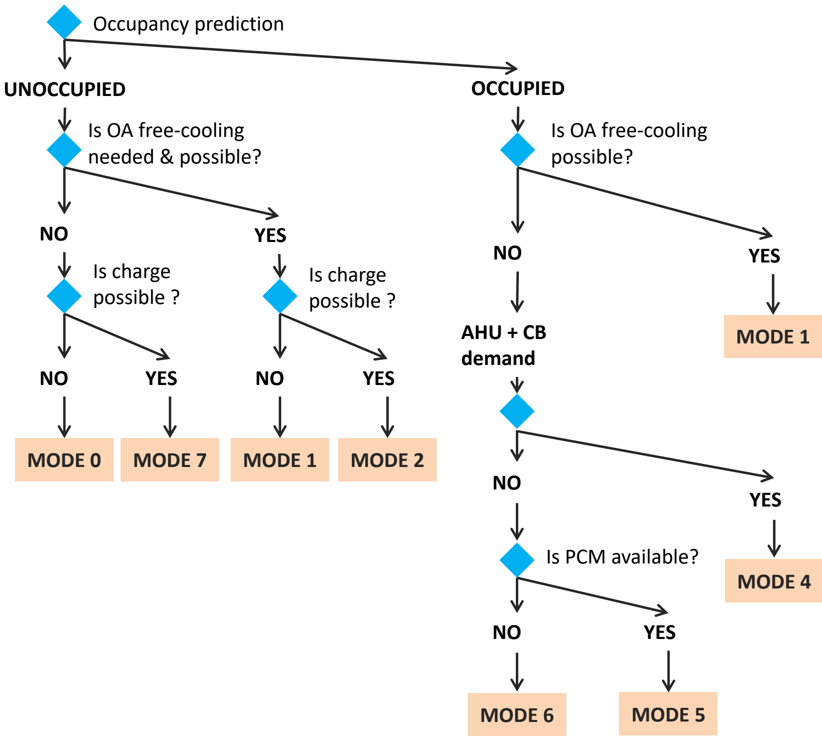


Figure 14. Operation modes scheme for Cool LowUp system

According to this control strategy, eight different operation modes have been defined. The main parameters determining which operation mode is selected are: occupancy, possibility to operate under free-cooling conditions and charge status of the PCM tank.

Every mode will be forced through the SCADA system to operate at least during one hour at steady conditions, unless forcing the operating conditions will jeopardize the integrity of the equipment or the normal activity of the building. For operation modes implying occupancy (i.e. 1, 4, 5, 6), relevant load conditions will be applied by using additional equipment (e.g. auxiliary reversible split units) when needed.

In order to check all the operation modes, input variables necessary to trigger the control systems will be forced in case the actual scenario (which depends in many situations on e.g. uncontrollable weather variables) does not correspond to the specific required values that should actually lead to a given mode. For instance, when outdoor air (OA) free-cooling conditions are not met, the variable or variables responsible for triggering operation modes implying OA free-cooling (i.e. mode 1 and mode 2) will be forced to evaluate that the control outputs are the expected ones according to the pre-defined control rules.

Each mode involves a different set of subsystems and auxiliary devices being turned on, and one of the purposes of the global system start-up is to check that the control strategy of whole system operates properly (not only from a subsystem perspective) and adequately commands the corresponding equipment involved in such operational modes.

2.1.3 Characterization of the system

After the start-up process is successfully completed, the **most relevant subsystems will be characterized on site to check that the design requirements are fulfilled, by comparing the outcomes of this phase with technical reports from manufacturers**.

Complementarily, these tests will provide additional data on the performance of these equipment, which will be of relevance for future systems due to their innovative character. In this case, the chiller, the PCM tank and the CB will be characterized. Before the execution of this characterization tests, the necessary sensing devices will have been installed in case they are not already included within the monitoring equipment.

The characterization of COOL-LowUP subsystems will be performed in two different stages: (1) individual tests for each of the most relevant subsystems, and (2) an indirect characterization test based on outcoming data from the normal operation of the system during the summer period (see 2.1.5). The main reason for this two-phase approach of the characterization process is based on the fact that the tests will be carried out in a real environment; hence, boundary conditions will not be completely controlled and may not be the desired ones for a proper characterization.

In every case, the readings from the tests will be processed and selected variables will be displayed in suitable way to facilitate the analysis of each subsystem's performance (e.g. two-axis plots, surface plots, tables, etc.).

2.1.3.1 Chiller

Despite the chiller does not constitute an innovative component of the COOL-LowUP solution, it has been decided to include it in the characterization phase in order to obtain a performance map associated to its operation, which, among others, will contribute to the fine tuning of the simulation models for the predictive capabilities of LowUP control solution.

The chiller is characterized by its 'Coefficient Of Performance' (COP). The COP curve/map must be obtained for different temperatures of produced cold water and different condensing conditions (which are normally determined in operation by the existing weather conditions and the cooling tower characteristics), and compared to specifications from the manufacturer. The nominal values are provided by the manufacturer; however, it is interesting to test the chiller working under different operating conditions.

The COP is defined as the ratio between the cooling energy output (at the evaporator) and the electric energy input consumed by the compressor. Thus:

$$COP_{chiller} = \frac{\dot{Q}_{evaporator}}{\dot{W}_{compressor}}$$

$Q_{evaporator}$: Power generated in the evaporator
$W_{compresor}$: Power consumed by the compressor

2.1.3.2 PCM Tank

To calculate the performance of the PCM Tank some laboratory tests were performed by the manufacturer (FAFCO) at their premises. An example of these tests and results comparison for ice and PCP10 latent storage discharge is shown in the following figure (D2.8 can be consulted for further information). It can be observed how maximum discharge power occurs at the initial phase of the discharge process when the difference between the water inlet temperature and charged PCM tank temperature is higher.

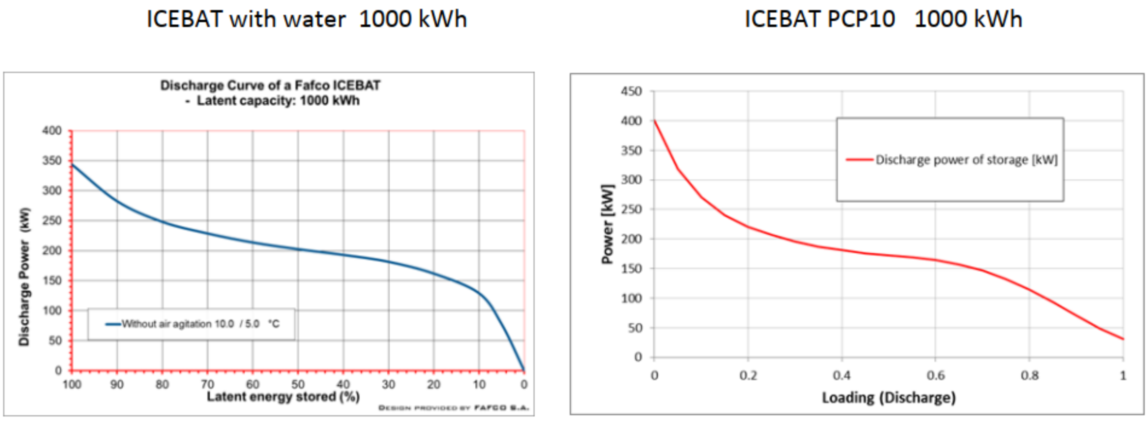


Figure 15. Example of performance chart for the PCM tank (source: ICEBAT storage by FAFCO)

The characterization tests of the LowUP PCM-based storage tank developed by FAFCO will provide experimental evidence to validate the modelling approach and simulation results derived from the storage model developed and presented in D2.2. The monitored charging and discharging curves will be compared with simulation results considering the same boundary conditions.

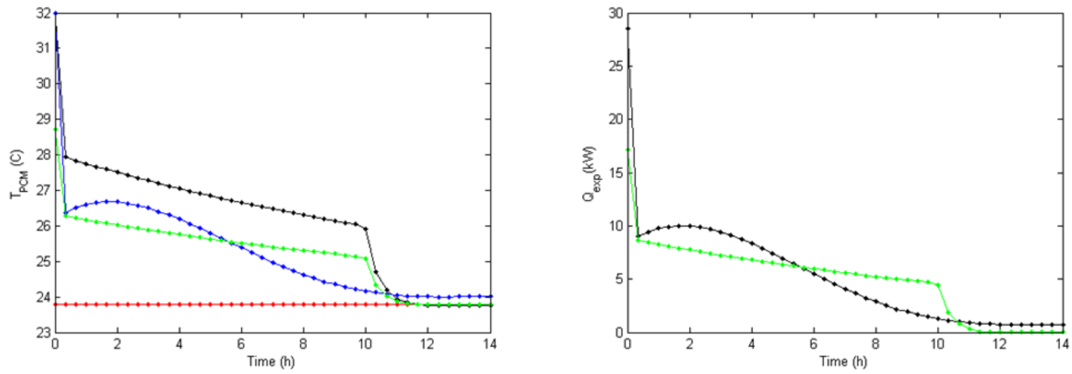


Figure 16. Simulation results from LowUP PCM model (see LowUP D2.2)

As it can be observed in the previous examples, the main variables to be controlled for the characterization tests of the PCM tank are:

(i) the water mass flow rate or water inlet/outlet temperature difference,
(ii) the water inlet temperature (which forces faster or slower charging/discharging processes),
(iii) the charging mode of the tank (either charge or discharge modes are possible and relevant for testing)

2.1.3.3 Chilled Beams

The chilled beams, similarly to the PCM tank, were tested at the manufacturer's facilities (HALTON). Depending on the cooling loads, the beams are modulated through a valve (i.e. one valve per each beam) and a damper. Results of the manufacturer test can be consulted in the deliverable D2.4. The figure below shows an example of this information:

Normal Cooling	REO/A-3600-A-2500		2016.09
Room:		Supply air flow rate:	8 x 24 l/s
Room size:	20.0 x 6.6 x 3.4 m		2.5 l/(sm²)
Occupied zone:	h=1.8 m / dw=0.5 m	Supply air temperature:	15.0 °C
Room air:	25.0 °C / 50 %	Static chamber pressure:	100 Pa
Heat gain:	910 W	Total pressure drop:	105 Pa
Installation height:	2.90 m	Total sound pressure level:	27 dB(A)
Inlet water temperature:	17.0 °C	Primary air capacity:	2332 W (8 x 291 W)
Outlet water temperature:	19.2 °C	Total cooling capacity:	9677 W (8 x 1210 W)
Water flow rate:	0.800 kg/s (8 x 0.100 kg/s)		367 W/m, 73 W/m²
Coil capacity:	7345 W (8 x 918 W)	Dew point temperature:	13.8 °C
	278 W/m	Velocity control:	side=3, middle=3
Water pressure drop:	11.4 kPa	Min flow opening:	67.4
		Normal/boost opening:	100.0 / 0.0
		L_d:	-

Velocity point	v1	v3		
Nozzle jet	~0.05 m/s	~0.20 m/s		
Nozzle jet, isothermal	~0.05 m/s	~0.10 m/s		
dt (nozzle jet-room air)	-0.2 °C	-0.9 °C		

Heat sources and their location may influence the velocity and direction of the jet

vlim = 0.20 m/s

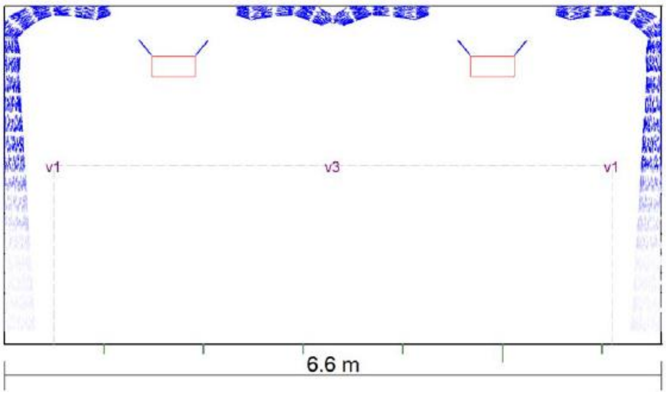


Figure 17: Example of results from a performance tests for CB from HALTON

In the demo site of Seville, new tests will be performed. Different days (i.e. different loads) and different supply water temperatures will be evaluated, while keeping static pressure in the ductwork as suggested by the manufacturer.

The performance of the Normal, Boost and Min. modes of the chilled beams will be also considered in order to compare results obtained on site vs. those provided by the manufacturer.

2.1.4 Operation and Validation

After the characterization tests, the system will be operated during a significant timespan under relevant conditions, i.e. at least one month of the summer period in automatic mode, with normal activity in the demo building in Seville.

Once this operation period is satisfactorily completed, a significant set of performance variables will have been monitored and recorded. These readings will constitute the reference values to obtain KPIs (Key Performance Indicators) which will be used both to complete the characterization of the subsystems (see section 2.1.3) and the validation of the simulation models that will be used into the Model Predictive Control approach.

Thus, the validation process will aim at evaluating the accuracy of the TRNSYS models (see T2.1) and will consist of successive comparisons of results for specific scenarios, both from the actual system and from the TRNSYS models, in order to refine the models and try to pair real and simulated performances.

Therefore, the outcomes of this validation process will be finer results of the TRNSYS models, hence more accurate representations of the actual system. A periodical revision of the models will be carried out to adjust any potential variation that may occur in the actual system to ensure both performances are accurately paired. The evaluation of the accuracy of the model will be performed making use of two statistic indexes which *ASHRAE Guideline 14-2014* clearly defines for calibrated models: Coefficient of Variation of the Root Mean Square Error (CVRMSE) and Normalized Mean Bias

Error (NMBE). These indexes, based on error measurements (i.e. the difference between simulated results and the actual energy data of the building), are defined as follows:

$$NMBE = \frac{\sum_{i=1}^{n}(m_i - s_i)}{n \cdot \bar{m}} \cdot 100\ (\%)$$

$$CVRMSE = \frac{\left[\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n-1}\right]^{1/2}}{\bar{m}} \cdot 100\ (\%)$$

m_i = measured value
s_i = simulated value
$\bar{m}$ = mean of measured values
n = number of measured data points

From the guideline, models based on actual monthly data should have a NMBE at 5% or lower and a CVRMSE of 15%, and for hourly data calibration, those two indexes should be 10% and 30%, respectively.

Due to the complexity of the system, these statistic indexes will be only applied to selected indicators which characterize each of the subsystems (e.g. CB, PCM Tank, Chiller/AHU).

Additionally, the validation of the COOL-LowUP solution performance as a whole will be conducted based on: (i) the average indoor temperature in the building, (ii) the energy provided by the LowUP system, and (iii) an overall energy performance index. These will be used as global indicators.

For what concerns the overall energy performance/efficiency: In the chiller evaporator the energy provided to the CB and the AHU is delivered (without considering distribution losses and performance of terminal units). Actual useful cooling energy output is delivered by the chilled beams. Besides, the energy consumption of the overall COOL-LowUP solution is associated not only to the chiller's compressor but also to the main auxiliary devices (i.e. pumps and fan). Therefore, in order to characterize and test the whole system, the global efficiency is calculated using this formula:

$$SEER_{COOL-LowUP} = \int_0^T \frac{\dot{Q}_{CBs}}{\dot{W}_{compressor} + \dot{W}_{pumps} + \dot{W}_{CT,fan}} \cdot dt$$

System or subsystem	Indicator description	Symbol	Units
Building (global performance)	Average indoor temperature	T_{indoor}	°C
Cool LowUP (integrated system)	Cooling power provided by the LowUp system; sum of power delivered by the cooling tower and the chiller	P_{cool}	kW
	Overall solution performance	$COP_{COOL-LowUP}$	-
Chiller/AHU	Cooling power delivered by the chiller	$P_{therm,chiller}$	kW
	Instantaneous Energy Efficiency Ratio	EER	-
	Seasonal Energy Efficiency Ratio	SEER	-
Cooling tower	Cooling power delivered by the cooling tower	$P_{therm,CT}$	kW
	Thermal wet-bulb effectiveness	ε_{wb}	-
Chilled beams	Total thermal power delivered by the CB (air+coil)	$P_{total,CB}$	kW
PCM storage tank	PCM discharge (load) thermal power	$P_{PCM, load}$	kW
	PCM charge (source) thermal power	$P_{PCM,source}$	kW

Table 1: KPI indicators for validation of Cool LowUP system

Only energy indicators will be used in the validation process. Any additional indicator such as economic or environmental indicators will be calculated based on previously presented parameters

Finally, the relevance of this validation process is linked to the need and value of the calibrated simulation models that will be used as a core part of the optimized control strategies as well as to develop supervisory algorithms (also at the core of the predictive maintenance strategy). The strategy will be based on the comparison of actual readings from the equipment with the expected performance derived from the calibrated models. These comparisons will contribute to indirectly highlight potential degradation of components. The quantification of the deviation between actual and expected performance will contribute to the prediction of potential failures, so maintenance tasks to avoid these events will be derived from this process.

2.1.5 Action plan

Activities described in previous sections will be integrated within an action plan, which will define a logical and systematic sequence for the different tasks to be followed. Despite this action plan includes specific timespans for each of the planned activities, these periods are subject to modifications depending on the actual development of the activities, and are to be considered as illustrative. For instance, a decisive factor that can modify the pre-planned development of these procedures is users' comfort during their activity in the building; hence, any task that may significantly affect the normal development of this activity will be adapted to avoid any relevant inconvenience.

Commissioning of the subsystems

The commissioning of the different subsystems which integrate the COOL-LowUP solution will be described in more detail into D4.12. The activities included in this phase (see section 2.1.1) depend on various factors, but the duration would not typically exceed two working day for each of the subsystems if the procedures are methodically followed and no complications occur.

Start-up of the global system

After the commissioning of the different subsystems separately, the start-up of the global system will be carried out, being the operation of the system under design conditions its first goal. Next, normal and acceptable conditions will be tested, together with the different operation modes. The complete phase is expected to take one week, although depending on the success in the checking process of the operating modes, some extra time may be needed. This set of activities and the commissioning of the subsystems can be carried out at any moment of the year, although design conditions of the system would be preferable.

Characterization of the system

- <u>Chiller</u>

The chiller will be operated following a controlled sequence which will allow to determine its performance map within a relevant range of operating conditions for the COOL-LowUP configuration. In particular, the characterization of the chiller will be based on testing its performance under varying load and source temperature conditions: (i) load side will be controlled at different evaporator water outlet temperatures supplying cooling energy to the AHU's cooling coil (to generate a controllable cooling load and obtain comparable conditions in terms of the water inlet/outlet temperature difference); (ii) source side will be controlled at different condenser water inlet temperatures that will be fixed as setpoints of the cooling tower water outlet temperature.

The table below provides the specific levels for the proposed characteristic parameters:

Parameter	**Unit**	**Specific levels to be tested**			
Condenser water inlet temperature	ºC	20	25	30	35
Evaporator water outlet temperature	ºC	7	10	13	16

Table 2. Levels of selected relevant variables for the characterization tests of the chiller

Both the load and source water mass flow rates will be set at the design values recommended by the manufacturer. Each of the specific scenarios will be operated during at least one hour. Average performance values will be obtained from every interval.

- <u>PCM tank</u>

During a set of consecutive days, a total cooling demand will be artificially created during the working hours i.e. from 9 a.m. to 21 p.m., by fixing the inlet water temperature to the PCM tank thanks to the AHU chiller operating in heating mode. Note that the AHU chiller is in fact a reversible equipment capable of delivering either cooling or heating; then, it will be used to create alternative charging/discharging cycles for the PCM tank characterization).

Particularly, during the discharging interval, the inlet temperature will range between 15°C (i.e. design operating temperature) and 35ºC (considered as the upper limit of a reasonable operating temperature range). During no-working hours, the tank will be re-charged at 10ºC, and the mass flow will be forced to the nominal value (see Figure 18).

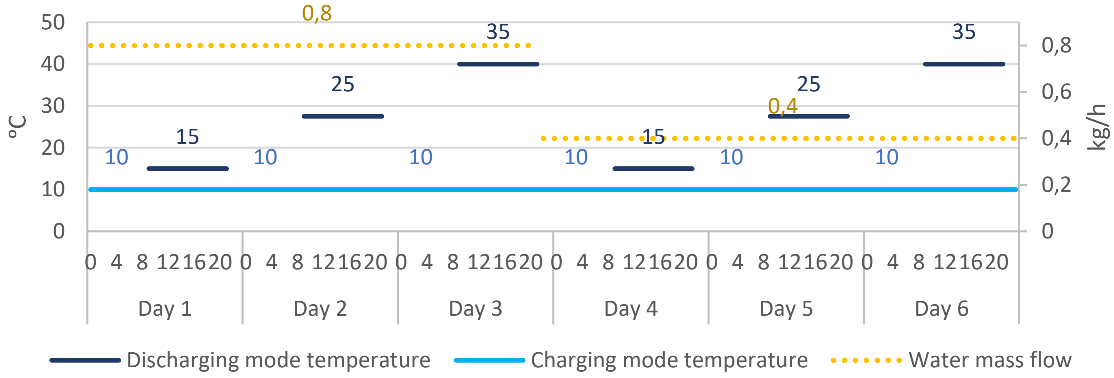


Figure 18. Charging and discharging temperature and water flow for the PCM tank characterization test

For the test period, the PCM tank will be freely operated to characterize the discharging and charging phases. In case the imposed temperatures jeopardize the integrity of the system at any moment, the test will be either adapted or aborted (e.g. in case temperature in the tank exceeds the maximum operating value or minimum charging level). Similarly, inlet water flow will be stopped in case the PCM tank reaches maximum charge level.

All variables included in the table below will be recorded during the test using the same timestep as for the general monitoring strategy; ranges of values represent the intervals that will be tested and missing values correspond to expected outcomes from the test. Parameters to be fixed during the tests are also explicitly specified.

	Inlet water temperature	Outlet water temperature	Ambient temperature	Charging mode	Water mass flow	Discharge cooling power	Charge power required	Charge status
Units	10-35 °C	°C	°C	Charge vs. discharge	[fixed] kg/h	kW	kW	%

Table 3: Variables to be recorded during the characterization test of the PCM tank

- <u>Chilled beams</u>

For the characterization tests of the CB, inlet water temperature and airflow operation modes will be modulated during the characterization tests. However, since the characterization of the CB will be directly performed inside the building, where conditions are difficult to be set at constant values, results from the tests are likely to offer a wide range of scenarios that cannot be directly compared with data from the manufacturer. For instance, temperature in the building will significantly affect the performance of the CB and will depend on external conditions and the effect of CB.

Similarly, the total thermal gain constituted by users and equipment (e.g. computers or lighting) will affect the results of the tests due to their relatively high variability depending on the activity at every moment of the day. For that reason, days with equal or similar and relatively constant gains will be selected. The thermal gains were initially estimated in D2.1, and will be revised based on information on occupancy, equipment and their uses along a typical summer week, and energy-conversion factors from reliable sources, e.g. 2013 ASHRAE Handbook Fundamentals, DIN EN 13779:2007, VDI 2078 (2015) or SIA 2024 (2015). However, actual variations on these gains during the recording period will deviate the readings from the estimates; hence, the accuracy of the characterization will be affected.

As part of the characterization test of the CB, next variables will be recorded and analysed. Those values stated as so will be fixed as constant parameters during the tests:

	Inlet water temp.	Outlet water temp.	Supply air temp.	Room temp.	Heat gain (est.)	Water flow rate	Coil capacity	Primary air capacity	Water pressure drop
Unit	16-20°C	°C	°C	25°C	[fixed[1]] kW	[fixed] 0.8 kg/s (8x0.1kg/s)			[fixed] kPa

Table 4: Variables to be recorded during the characterization test of chilled beams

Specific characterization tests will be complemented with data resulting from the continuous-operation period programmed for the validation of the models, but only if previous tests do not provide the expected results. Therefore, there will not be a specific interval for this task within the action plan, but it will be developed along with the operation of the system; only if necessary (i.e. if conditions for specific tests enable proper characterization of every subsystem, results from the operation period will not be further analysed to support such characterization).

Operation and validation

The operation of the system in automatic mode will start as soon as the previous phases are completed, and will be conducted under cooling operation conditions during the summer period in 2020. The start of the validation phase, which will use the outcomes of the operation period, can start after a significant interval of time has been monitored. The decision on the exact amount of time before starting the validation will depend on the criteria of the technician in charge of the system, but one week after transient conditions can be a reasonable period. Thus, an iterative validation process will allow refining models along with data being recorded. After the operation period is completed, the validation phase may extend for some extra weeks depending on the matching process of real and modelled systems.

Next, a Gantt chart summarizes the sequence of main activities included in this action plan (dates are expressed in days).

System	Task/Subtask	Duration	Start	End
Cool LowUP	**2.1.1 Commissioning of each system**	**8**	**1**	**8**
	· Chiller/AHU	2	1	2
	· PCM Tank	2	3	4
	· Chilled beams	2	5	6
	· Cooling Tower	2	7	8
	2.1.2 Start-up of the global system	**5**	**9**	**13**
	· Start-up phase	2	9	10
	· Operation modes	3	11	13
	2.1.3 Characterization of the system	**21**	**14**	**34**
	· Chiller/AHU tests	7	14	20
	· PCM Tank tests	7	21	27
	· Chilled beams tests	7	28	34
	2.1.4 Operation and validation	**66**	**35**	**100**
	Automatic operation	66	35	100
	Validation process	59	42	100

Figure 19. Proposed Gantt for the commissioning, start-up, characterization and operation of COOL-LowUP

[1] As previously exposed, internal thermal gains are not easily controllable in a real environment and may vary significantly during working hours. However, efforts are advisable to keep them as stable as possible.

2.2 Heat LowUP System

The Heat-LowUP solution is constituted by five main systems: (i) PV/T solar field and (ii) thermal emulator of the waste heat recovery unit, as the two key systems to capture low-exergy sources; (iii) an air-to-water HP as back-up generation system; (iv) the stratified thermal storage tank; and (v) the radiant floor system (which constitutes the heating terminal units of the solution).

Additionally, a dry cooler is included in Seville's demo site for heat rejection, in order to emulate higher heating loads and analyse scalability opportunities. In the image below, a simplified diagram of the facility is shown:

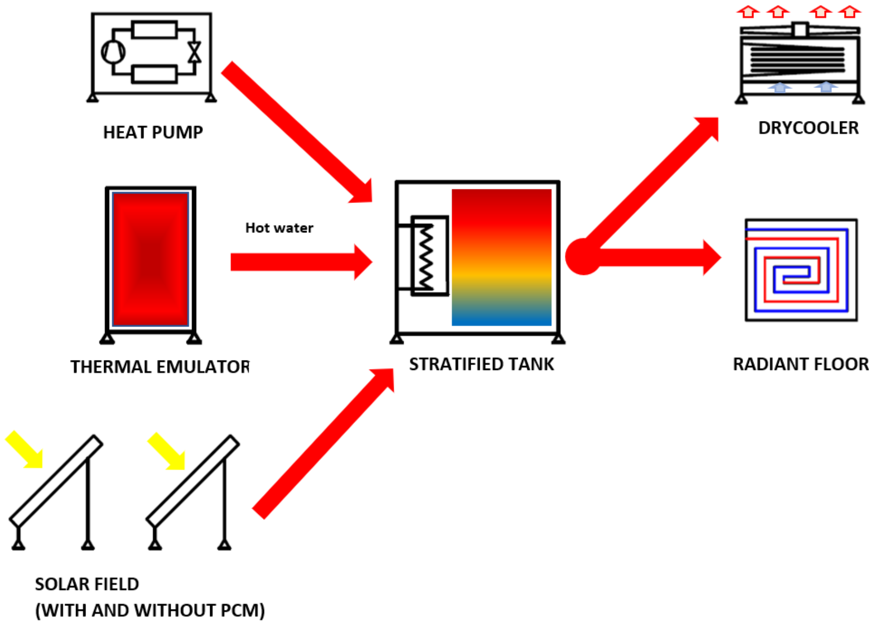


Figure 20: Heat LowUP – Concept diagram

The solar field, during sunny days, produces electricity to be self-consumed used in the building facilities and heats up the water which enters the stratified tank from above. A heat pump is also connected to the tank, and provides hot water when solar field cannot cover the heat demand of the building. Additionally, a thermal emulator is integrated and connected to the tank to reproduce the operation of the grey-water heat recovery (ECOWEC system, see D2.6). Hot water from the stratified tank is supplied into the low-temperature radiant floor, which distributes heat inside the building, and connects the return flow to the bottom of the stratified tank. Finally, as stated previously, a dry cooler is included in the demo site system to emulate higher thermal demands.

The following images offer an overview of the integration of the main systems in the plant, as well as the complementary systems (i.e. thermal emulator and dry cooler):

Figure 21: Low-temperature Radiant floor integration

Figure 22: Heat pump integration

Figure 23:Solar field (PVT panels with and without PCM) integration

Figure 24: Dry cooler integration

Figure 25: Stratified Tank integration

Figure 26: Integration of the thermal emulator (to represent the performance of the grey-energy heat-recovery system)

2.2.1 Commissioning of each system

As for the COOL-LowUP solution, this section aims to summarize generic operations regarding the commissioning of each HEAT-LowUP subsystem to be performed by qualified balancing and start-up technicians (only authorised service centres). The commissioning process will include the setting up, balancing, adjustment, start-up and testing of each subsystem, to ensure that all the requirements are met as specified by manufacturers. This procedure is set to be completed before operation and validation of the system once all the elements are integrated. Start-up checklists (provided by manufacturers) for every equipment will be followed and will be always prioritised; hence, following operations are just a reference to complement specific steps included in official installation and use manuals or to guide the start-up process in case use manuals do not exist. Any additional operation from start-up checklists and other manufacturer guidelines will be included in the start-up process.

Before and after the start-up of every subsystem a general checklist must be applied, as previously detailed (see section 2.1.1). Next, specific operations to be included during the start-up phase of each of the main HEAT-LowUP subsystems are presented.

2.2.1.1 PV/T Solar Field

In the case of the PVT solar field, several additional checking operations must be performed before, during and after the start-up procedure. Complementary checklist before the start-up:

- Installation is consistent with schematic diagram, documentation and physical layout diagram; the position of solar panels is correct in terms of tilt and orientation so that annual performance is optimized according to pre-design simulations. Absence of unexpected shading elements.
- Racking is straight, square, neatly trimmed and fully tightened. Modules are tightly attached to the mounting structure according to instructions from the manufacturer and the approved plans; steel fasteners.
- Modules are in good condition, i.e. no broken glass or cells, no discoloration, frames not damaged, perfectly cleaned surfaces.
- A complete grounding electrode system is installed, and modules are grounded using the grounding point in accordance with requirements.
- DC and AC disconnects are permanently installed and readily accessible.
- All wiring is neat, tidy, and left at appropriate service loops lengths (no loose strands, wiring not readily accessible). Wire insulation is not scuffed or broken.
- All electrical components are labelled and listed (including serial number, rated voltage and current) and meet required standards; inverter and modules meet minimum warranty requirements, wire sizes and type match pre-installation design specifications.
- Modules are covered to prevent heating (or commence the fill at night when collectors are cool).
- Pipe insulation is properly sized to fit pipe and continuously closed and sealed.

After the start-up:

- Average output power from inverter display after inverter is stabilized.
- The power output is within expected values according to weather conditions.

2.2.1.2 Low-Temperature Radiant Floor

The commissioning of the LowUP low-temperature radiant floor system will be performed in accordance to the common practice for general hydronic systems. In particular, the recommendations and templates for the reporting of the commissioning process according to the Spanish regulatory framework will be considered as guidelines (IDAE, 2014)

Therefore, the main principles to be applied to the inspections of the system before the start-up of the overall solution will focus on: (i) system filling and cleanliness, (ii) air removal, (iii) commissioning of control systems, (iv) functional checks for in-built elements (mainly pumps and valves), and (v) hydraulic balancing.

- **System filling and cleanliness**

In the design stages, adequate provision must be given to the removal of all extraneous matter by flushing out the system. Dirt and air can adversely affect the accuracy of the measuring instruments used to perform the balancing process.

After hydrostatic pressure tests are approved and prior to putting the system into operation, the system should be drained and immediately refilled with a solution of water containing a non-foaming alkali detergent. The solution should be circulated continuously for a minimum of 16 hours, cleaning the strainer as required. On completion, the system is drained again, refilled with fresh water and circulated for further two hours. The system can then be drained and refilled with water and chemical treatment to establish the correct pH level. On larger installations the cleaning of the system may be achieved by the continuous removal of water while the system is running over 24 hours, taking care to monitor the discharged water to establish an adequate state of cleanliness.

- **Air removal**

Removal of air is also of the utmost importance to minimise corrosion; therefore, extraction provision should also be allowed for in the design stages.

Automatic vents can be used on the sealed heating circuit. They should be located at all high points where the air will collect naturally. The best locations are within the water system where the highest temperature and lowest pressure occurs.

- **Commissioning of control systems**

The commissioning of the local control system provided by RDZ will be done according to the manufacturer's recommendations by checking that the different control modes are available and setpoint modifications lead to the expected control actions.

Moreover, since the local control will be connected to the overall HEAT-LowUP SCADA, this connection will be also checked during commissioning, ensuring proper communication of read/write variables as well as adequate access to the relevant setpoints (i.e. room temperature setpoint, water supply temperature, pump on/off signal).

Finally, the overall control system (integrating the operation of the radiant floor with the rest of the HEAT-LowUP subsystems) will be described in Section 2.2.2

- **Functional checks on pumps and valves**

This includes pumps, valves, filters, sensors and actuators of the heating system. Particularly, check the correct rotation direction in elements where this makes sense.

The operation of the pump(s) can be checked by touch (if the pump is operational, you can feel slight vibration at start-up) or by closing the pump's valves where there has to be a change in pressure on the pressure indicators (manometers), there can also be minor pressure thrusts on the pipeline. Perform the closing of valves carefully so as to avoid damaging the pump (follow the instructions of the pump's manufacturer).

- **Hydraulic balancing**

The adjustment and balancing of the low-temperature radiant floor circuit consists of ensuring that each radiant floor loop receives its nominal flow, with a maximum deviation that should not exceed 10%[2] of the design flow established in the Project Report.

2.2.1.3 Stratification Storage Tank and Thermal Emulator

The start-up operations of the Stratification Storage Tank and the Thermal Emulator are relatively similar and simple; hence, only one section has been included for both subsystems. Complementarily to the operations already included in previous section, before and during the start-up some activities must be carried out. Complementary checklist before the start-up is:

- The ground load-bearing capacity is guaranteed for the expected load (plus a safety factor). The ground must be flat and level.
- Visual absence of corrosion and physical damage.
- The tank interior is clean and free of sediment. Disinfection is also recommended as part of the start-up procedure.
- All ports and valves are positioned or connected as detailed in specifications from the manufacturer and fulfil design requirements.

During the start-up the following aspects will be checked:

[2] It is suggested that the heating water flow rate should be between ±10 % of design, even though normal hot water systems can tolerate a wider flow deviation. The ±10 % tolerance is economically achievable, and can eliminate side-effects caused by issues such as low water velocity and air purge problems. However, terminals using low temperature hot water as found in heat recovery systems may require the tolerance to be within ±5 % of design flow rate.

- Absence of leakages, especially in ports, valves and distribution and connection elements.
- Pressure levels during filling and emptying processes are as expected (and recorded).
- Electrical backup heaters operate properly, including control modes.
- In the case of the stratification storage tank, the stratification columns operate properly, i.e. the higher is the inlet water temperature, the higher it enters the tank along the vertical dimension.

2.2.1.4 Heat Pump

The HEAT-LowUP backup heat pump is a commercial product whose commissioning will be realized according to the specific recommendations of the manufacturer. General recommendations for heating and cooling facilities will be followed. In particular, the most relevant procedures and inspections to be performed and verified at the commissioning of the heat pump are listed below:

- Checking the **compatibility of the hydraulic piping** with the piping diagrams recommended by the manufacturer
- Checking the correct **operation of all built-in elements**

This includes pumps, valves, filters, sensors and actuators of the heating system. Particularly, check the correct rotation direction in elements where this makes sense.

- Checking **electrical connections and settings**

This will be done according to the wiring diagrams that must be provided by the contractor of the installation. Moreover, the correct settings of the parameters of the heating system, heating curves, heating circuits, thermostats, spatial correctors, and other parameters must be set according to the heating system in the building.

- Checking the **presence of air** in the system, **system filling** and pressure levels

Check if air is present in the heating system and remove it with the vents in the system. After venting check the pressure of the heating medium in the heating system and raise it as needed with a supplementation of the medium. For the filling process the manufacturer's instructions for installation, use, and maintenance must be followed. The installation may only be commissioned if the heating system and water heater have been filled and bled. Otherwise the circulation pump can be damaged.

- Checking heat **insulation** of pipe connections
- Preparing the system for start-up

Before turning the device on, check the water temperature in the heating system. At start-up it has to be 20 °C or more, otherwise problems could arise at commissioning or with the device's operation.

- Checking the operation of the **heat source**

Checking the operation of the heat source during start-up of the device serves as additional control of the execution of the pump's electrical connection, hydraulic connection, and cleanliness of the filter and ventilation of the system on the primary side of the device. Turn on the pump(s) on the primary side of the HP. The operation of the pump(s) can be checked by touch (if the pump is operational, you can feel slight vibration at start-up) or by closing the pump's valves where there has to be a change in pressure on the pressure indicators (manometers), there can also be minor pressure thrusts on the pipeline. Perform the closing of valves carefully so as to avoid damaging the pump (follow the instructions of the pump's manufacturer).

- Checking the **operation of heating/cooling the water in a buffer tank**

Functional testing of the operation of heating/cooling the water is performed by trying to heat/cool the heating cycle with the smallest volume or in case the system has an external buffer tank, by closing the valves on the water side behind the buffer tank towards the users/consumers.

After turning on the device, wait for 5 to 10 minutes for the device to reach stable operation. Afterwards, check if an adequate temperature difference occurred (3 to 6 °C) between the supply and return line. Set the appropriate speed of the pump being careful not to lower below the NO WATER condition/error. The most frequent reason for (too) high temperature difference is a blocked strainer, insufficient ventilation of the system and inadequately chosen pump.

After checking the hydraulic system, inputting the parameters and resolving eventual errors, the **handover documentation** for the performed or aborted start-up should be filled out.

2.2.2 Start-up of global system

After completing the commissioning process for all subsystems individually, the complete solution will be evaluated as a whole in order to check the proper performance and integration of subsystems. This phase comprises the start-up and shut-down of the global system and a sequence of operation, which includes the same start-up activities as for COOL-LowUP solution: system operation in automatic conditions, alarms and operational safety checks. Complementarily, the triggering of all the operation modes will be checked. Results from these activities will be adequately registered. Additionally, the correct triggering of the different **operational modes will be verified** as planned in the previous phases.

At a first stage, the system will be run under design conditions to evaluate the proper performance of all the constituent elements. At a second stage, the system will be forced to operate beyond setpoints and reach alert and action limits (see Figure 12 in section 2.1.2). This procedure will contribute to check key performance aspects such as fault detection system, communication limits, operational gaps, programming errors, transitory states or reliability and robustness of the system, among others.

As previously stated, each subsystem (i.e. PVT solar modules, Low-temperature Radiant Floor, Stratified Storage Tank) are conformed by a set of devices (e.g. pumps, valves, fans), and all these devices are controlled by the subsystems' PLCs. A front-end PLC will act as the "brain" of the global system, and will be in charge of sending orders to the subsystems' PLCs in the form of setpoints. Apart from controlling the subsystems, the front-end PLC is also responsible for sending orders to the auxiliary devices (e.g. pumps, valves) which do not belong to any subsystem. **The proper execution of the control strategy programmed in the front-end PLC will be checked during the start-up phase**.

All the operation modes will be checked, and in case the actual scenario does not meet the required conditions, input variables necessary to trigger the control systems will be forced to evaluate that control signals in the elements involved in these modes are the expected ones.

Through the start-up of the global system, the control strategy will be validated not only from a subsystem perspective but from an overall perspective, and will ensure that the different sets of subsystems and auxiliary devices involved in each mode are properly configured.

Start-up activities will be constituted by a sequence of tasks to validate the proper operation of the system for all the operation modes that have been programmed via the controlled variation of relevant parameters during a significant timespan.

As previously stated, present document does not aim to describe in detail the control strategy, however a brief summary is included in Figure 27.

According to the control strategy, four different operation modes have been defined for the HEAT-LowUP system depending on the boundary conditions. The main parameters that determine which operation mode is selected are: the operation schedule of the radiant floor, the heating demand and the temperature of the stratification storage tank (Figure 27, see D2.10 for a detailed description).

As planned for COOL-LowUP solution, the SCADA system will be the core element to force all modes integrated in the control strategy, and each mode will be operated during at least one hour under steady conditions, unless this process will jeopardize the integrity of the equipment or the normal activity of the building. For operation modes implying heating demand (i.e. 3, 4), minimum, average and maximum loads will be evaluated during a significant timespan and additional equipment will be used when necessary to represent thermal loads equivalent to expected occupants.

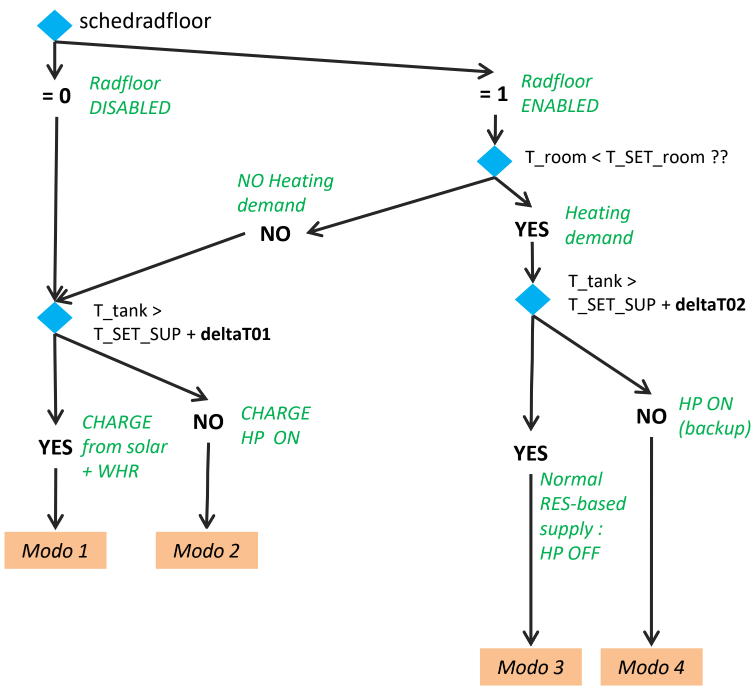


Figure 27. Operation modes scheme for HEAT-LowUP system

2.2.3 Characterization of the system

The characterization of the system will be tackled similarly as for COOL-LowUP system (see 2.1.3). Thus, the most relevant subsystems will be characterized on site once the start-up process is successfully completed. Results from the on-site test will be compared with technical reports from manufacturers to check that the design requirements are fulfilled. In this case, the PVT solar field, the low-temperature radiant floor and the stratified storage tank will be object of the characterization.

The main stage of the characterization phase will be the development of specific tests for each of the above-mentioned systems. Since expected conditions for these tests may not correspond to actual conditions during the planned tests, a second input for the characterization of the system will be included. This input will be constituted by the readings from the operation of the system during winter period for the validation of the models (see 2.2.4). The readings from all of the tests will be processed to ensure that the values to be compared with data from manufacturers share equal or very similar conditions.

2.2.3.1 PV/T Solar Field

The solar field includes two different configurations, i.e. PVT hybrid modules with PCM integration and without PCM integration, but characterization tests will be developed following equal procedures to compare both performances. Due to the thermoelectric nature of PVT system, the characterization typically includes the calculation of both thermal and electrical efficiencies.

Electric subsystem (PV)

The characterization of the electric subsystem (i.e. photovoltaic modules) is typically carried out through the PR (performance ratio) of the solar field, and the PV efficiency factor under STC (Standard Test Conditions) or NOCT (Nominal Operating Cell Temperature).

The PR measures the quality of a PV plant independently of the incident irradiation and the orientation. This parameter relates as a percentage actual and theoretically possible energy outputs, and allows the comparison between different plants at different locations. For this case, the PR was estimated in 80% for Heat LowUp during the design phase (see D4.3):

$$PR = \frac{Actual\ reading\ of\ plant\ output\ in\ kWh}{Calculated, nominal\ plant\ output\ in\ kWh} \%$$

$Calculated, nominal\ plant\ output\ in\ kWh$ is the "target yield" considering the effective area of the modules, their efficiency and the solar insolation on surfaces

The efficiency factor of the PV modules under STC conditions has been provided by the PV manufacturer, and specifically has been reported as 16.7% (see Table 5). Since this factor has been obtained in a laboratory environment for STC only and these conditions are difficult to be reached in a controlled manner in real environment, this parameter will not be obtained onsite again.

ELECTRICAL SPECIFICATIONS (2)		
ELECTRICAL CHARACTERISTICS AT STC		
Nominal Power (P_{mpp})	[Wp]	275
Voltage at Nominal Power (V_{mpp})	[V]	31.5
Current at Nominal Power (I_{mpp})	[A]	8.74
Open Circuit Voltage (V_{OC})	[V]	38.7
Short Circuit Current (I_{SC})	[A]	9.25
Power tolerance	[-]	0±5 Wp
Module Efficiency	[%]	16.7
ELECTRICAL CHARACTERISTICS AT NOCT		
Nominal Power (P_{mpp})	[Wp]	202
Voltage at Nominal Power (V_{mpp})	[V]	28.8
Current at Nominal Power (I_{mpp})	[A]	7.02
Open Circuit Voltage (V_{OC})	[V]	36
Short Circuit Current (I_{SC})	[A]	7.4
TEMPERATURE CHARACTERISTICS		
Nominal Operating Cell Temperature (NOCT)	[°C]	45.7 ±2°C
Temperature Coefficients of P_{mpp}	[%/°C]	-0.4
Temperature Coefficients of V_{OC}	[%/°C]	-0.031
Temperature Coefficients of I_{SC}	[%/°C]	0.05
ADDITIONAL CHARACTERISTICS		
Maximum Reverse Current	[A]	25
Junction Box Protection Level	-	IP67

(2) Electrical characteristics provided by the PV manufacturer

Table 5: Electrical specifications of the PVT modules installed in Seville demo site

Thermal subsystem (heat recovery kit)

In the case of the thermal subsystem of the PV/T field, the characterization is usually based on the determination of the useful thermal energy provided by the collectors to the fluid under different operating conditions:

$$\dot{Q}_{PVT} = C_{p,w} \cdot \dot{m_w} \cdot \Delta T = C_{p,w} \cdot \dot{m_w} \cdot (T_{inlet} - T_{outlet})$$

being:

$C_{p,w}$	Isobaric specific heat for water, 4.18 kJ/(kg·K)
$\dot{m_w}$	Water flowrate in the solar system
T_{inlet}	Water temperature at the inlet of the solar field
T_{outlet}	Water temperature at the outlet of the solar field

This will allow defining a thermal performance index (thermal collector efficiency) as follows:

$$\eta_{th,PVT} = \frac{\dot{Q}_{PVT}}{\dot{Q}_{tot,incident}} = \eta_0 - a_1 \frac{T_m - T_a}{G}$$

being:

η_0	Collector optical efficiency (-)	T_m	Mean water temperature (ºC)
a_1	Collector heat loss coefficient ($W \cdot m^{-2} \cdot K^{-1}$)	T_a	Ambient temperature (ºC)
G	Total irradiance ($W \cdot m^{-2}$)		

Examples of experimental results obtained from the lab tests conducted by EndeF on the first PV/T collector prototype are provided below:

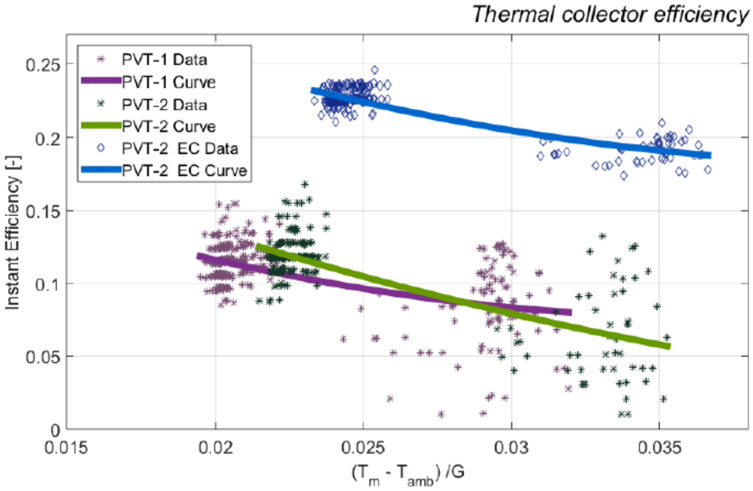


Figure 28: Example of results from the characterization tests for PV/T panels without PCM (ENDEF)

The on-site characterization test of the PV/T subsystem will be aligned to those performed by the manufacturer under controlled conditions (see D2.5), in order to ease the possibility to directly compare outcomes from both evaluations:

- For the thermal subsystem, in order for a steady-state test method to be applied onsite, there must be no significant wind in the selected interval. Otherwise, quasi-dynamic testing will be necessary.
- In case of the PV subsystem, the characterization will be based on the Performance Ratio (PR), but not in a yearly but an hourly basis. PR describes the relationship between the actual and theoretical energy outputs of the PV system. It shows the proportion of the energy that is actually available for export to the grid after deduction of energy loss[3]. The following figure represents the kind and relevance of most common energy losses in PV systems.

[3] In real life a PR = 100% cannot be achieved due to the existence of unavoidable losses. High-performance PV plants can however reach PR = 80%

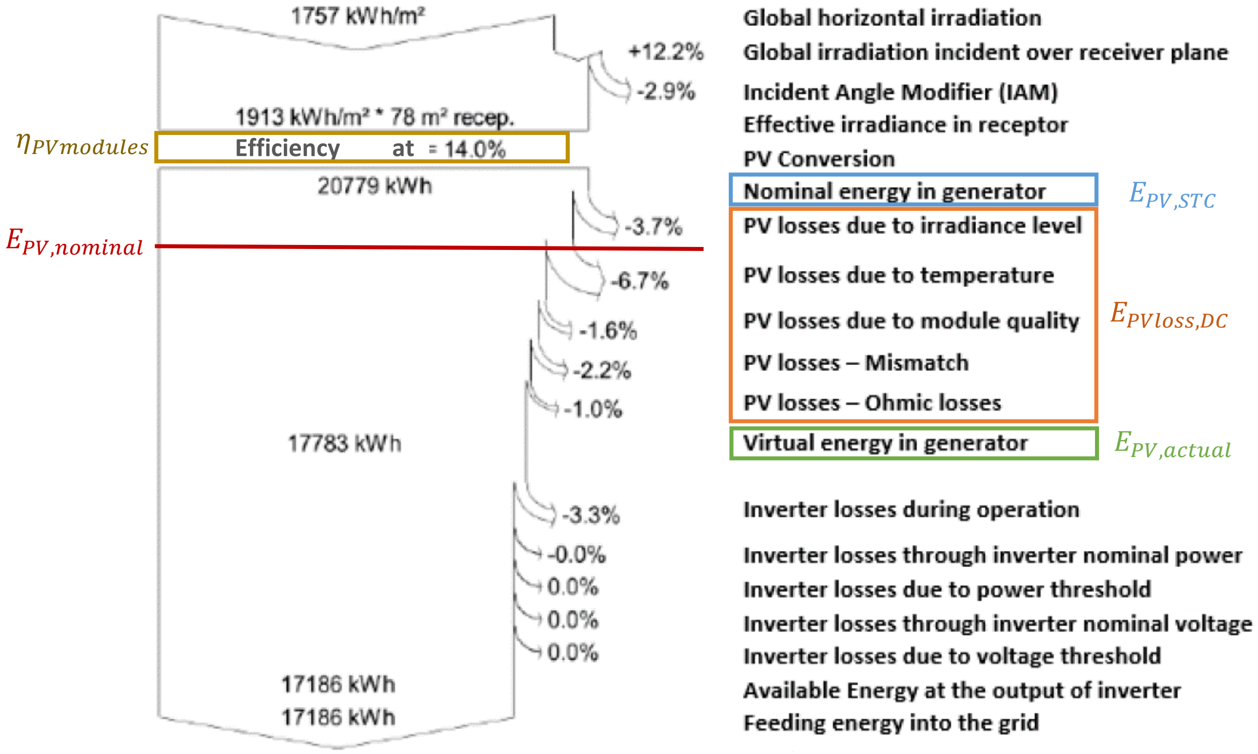


Figure 29: Example of estimated energy losses in the PV subsystem (see D4.3)

The difference between the actual PV output ($E_{PV,actual}$) and the theoretical one ($E_{PV,STC}$) is due to losses ($E_{PVloss,DC}$) associated to: (i) irradiance levels, (ii) temperature levels, (iii) module quality loss, (iv) light induced degradation, (v) module array mismatch, and (vi) ohmic wiring loss:

$$E_{PV,actual} = E_{PV,STC} - E_{PVloss,DC}$$

being $E_{PVloss,DC}$ constituted by the sum of specific losses due to irradiance levels different to standard conditions ($E_{irr\ loss}$), modules temperature losses ($E_{temp\ loss}$), module quality losses ($E_{mod.qua\ loss}$), Light Induced Degradation ($E_{LID\ loss}$), module array mismatches ($E_{mis\ loss}$) and ohmic wiring losses ($E_{ohm\ loss}$):

$$E_{PVloss,DC} = E_{irr\ loss} + E_{temp\ loss} + E_{mod.qua\ loss} + E_{LID\ loss} + E_{mis\ loss} + E_{ohm\ loss}$$

Since irradiance level will be measured and monitored, the nominal output of the PV plant will be estimated, equivalent to the target yield of the solar field (see Figure 29):

$$E_{PV,nominal} = E_{PV,STC} - E_{irr\ loss}$$

Finally, the performance ratio (PR) is obtained by dividing actual and target outputs under real conditions:

$$PR = \frac{E_{PV,actual}}{E_{PV,nominal}}$$

Therefore, the simple steps for the calculation of the PR are:

(i) Determine the theoretical energy output from the PV field for the reported period of time based on: measured average solar irradiation intensity ($G_{average}$, kWh/m²), PV area (A_{PV}) and PV efficiency provided by manufacturer ($\eta_{PVmodules}$, 16.7% in this case).

$$E_{PV,nominal} = G_{average} \cdot A_{PV} \cdot \eta_{PVmodules}$$

(ii) Consider the actual electrical energy produced by the PV plant ($E_{PV,actual}$ measured).

(iii) Calculate the performance ratio.

2.2.3.2 Low-Temperature Radiant Floor

To calculate the performance of the low-temperature radiant floor some laboratory tests have been carried out under controlled conditions in the manufacturer facilities (RDZ). An example of these tests is showed in Figure 30 (see D4.4 for more information).

Test method (Clause 9)

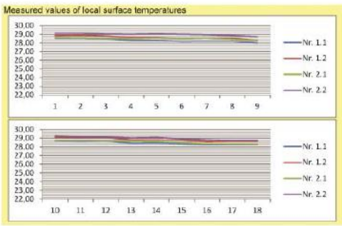
Measured values

Measurement No		1.1	1.2	2.1	2.2	
Heat conduction resistance of the covering (m² K/W)	$R_{\lambda,B}$	0	0	0,15	0,15	
Local floor surface temperature	$\vartheta_{F,1}$	28,53	28,86	28,61	29,14	°C
	$\vartheta_{F,2}$	28,56	28,90	28,59	29,13	°C
	$\vartheta_{F,3}$	28,48	28,82	28,51	29,02	°C
	$\vartheta_{F,4}$	28,31	28,66	28,50	29,00	°C
	$\vartheta_{F,5}$	28,31	28,66	28,57	29,05	°C
	$\vartheta_{F,6}$	28,16	28,50	28,49	29,00	°C
	$\vartheta_{F,7}$	28,19	28,57	28,56	28,95	°C
	$\vartheta_{F,8}$	28,19	28,52	28,40	28,86	°C
	$\vartheta_{F,9}$	27,99	28,31	28,29	28,75	°C
	$\vartheta_{F,10}$	28,72	29,08	28,75	29,25	°C
	$\vartheta_{F,11}$	28,64	29,03	28,72	29,15	°C
	$\vartheta_{F,12}$	28,68	29,06	28,71	29,15	°C
	$\vartheta_{F,13}$	28,43	28,81	28,63	29,03	°C
	$\vartheta_{F,14}$	28,45	28,81	28,61	29,07	°C
	$\vartheta_{F,15}$	28,39	28,78	28,50	28,94	°C
	$\vartheta_{F,16}$	28,24	28,60	28,37	28,81	°C
	$\vartheta_{F,17}$	28,26	28,64	28,33	28,74	°C
	$\vartheta_{F,18}$	28,26	28,64	28,32	28,74	°C
Heat water supply temperature	ϑ_V	38,31	39,02	52,69	54,34	°C
Heat water return temperature	ϑ_R	38,05	38,72	52,32	54,00	°C
Outlet cooling water temperature	$\vartheta_{C,out}$	20,07	20,10	20,09	20,13	°C
Inlet cooling water temperature	$\vartheta_{C,in}$	19,91	19,95	19,95	19,98	°C

Case of application (Part 5)		Floor heating
Heat transfer coefficient	α	10,8000 W/(m²K)
Additional thermal transfer resistance	ΔR_a	0,0000 (m²K)/W

Calculated values and results

Measurement No.		1.1	1.2	2.1	2.2	
Heat conduction resistance of the covering (m² K/W)	$R_{\lambda,B}$	0	0	0,15	0,15	
Maximum floor surface temperature	$\vartheta_{F,max}$	28,72	29,08	28,75	29,25	°C
Average floor surface temperature	$\vartheta_{F,m}$	28,38	28,74	28,53	28,99	°C
Average temperature of the heating medium	ϑ_H	38,18	38,87	52,51	54,17	°C
Average temperature of the cooling plates	ϑ_i	19,99	20,03	20,02	20,06	°C
Temperature difference	$\vartheta_{F,max} - \vartheta_i$	8,73	9,06	8,73	9,20	K
Temperature difference	$\vartheta_{F,m} - \vartheta_i$	8,39	8,71	8,51	8,94	K
Temperature difference	$\vartheta_H - \vartheta_i$	18,19	18,85	32,49	34,12	K



Heat conduction resistance of the covering (m² K/W)	$R_{\lambda,B}$	0	0,05	0,1	0,15	
Equivalent heat transmission coefficient	$K_{H,Floor\ heating}$	5,115	4,079	3,392	2,903	
equiv. heat transmission coeff. (case of application)	K_H	5,115	4,079	3,392	2,903	
Standard specific thermal output	q_N	95,8	96,2	96,6	97,0	W/m²
Standard temperature difference	$\Delta\vartheta_N$	18,73	23,50	28,49	33,43	K

Limit curves

Occupied area

Factor	φ	1,00			
Heat conduction resistance of the covering (m² K/W)	$R_{\lambda,B}$	0	0,05	0,1	0,15
Limit temperature difference	$\Delta\vartheta_{H,G}$	18,73	23,50	28,49	33,43
Limit specific thermal output	q_G	95,8	96,2	96,6	97,0

Peripheral area

Factor	φ	1,75			
Heat conduction resistance of the covering (m² K/W)	$R_{\lambda,B}$	0	0,05	0,1	0,15
Limit temperature difference	$\Delta\vartheta_{H,G}$	32,86	41,38	49,97	58,64
Limit specific thermal output	q_G	168,1	168,8	169,5	170,2

Project dates

Project No.	DRY HP PE
Client:	RDZ
Date of performance of calculation:	09.10.2017

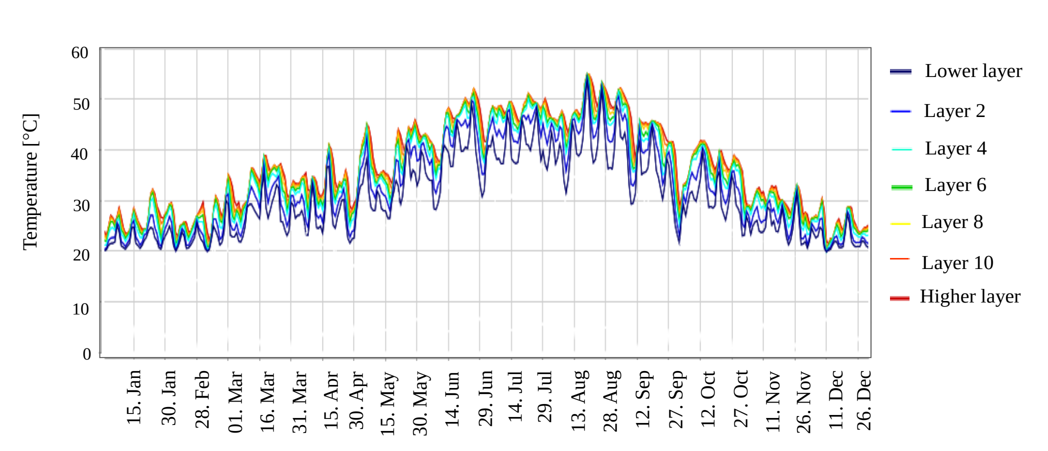
Figure 30: Example of a performance test of the radiant floor from the manufacturer (RDZ)

The characterization procedure to be followed in the demo site of Seville will be based on this test performed by the manufacturer, but some simplifications will be considered derived from the real environment. The main variables that will be monitored will be: (1-2) the water inlet and outlet temperatures, (3) the room temperature and (4) water mass flow. The behaviour of the radiant floor will be evaluated for different inlet water temperatures and water mass flow rates.

2.2.3.3 Stratified Tank

The characterization of the storage tank will be focused on its innovative aspect, i.e. water stratification capacity. A specific test to evaluate the stratification in the tank has not been previously performed by the manufacturer under laboratory conditions, but the thermal performance of the tank along its height has been analytically modelled within the project (see D2.7).

As resulted from simulations, maximum stratification between highest and lowest layers in the tank enhanced by vertical columns and horizontal diffusers is expected to reach between 18 and 28°C in the tank, compared to 2-5°C in a standard tank:



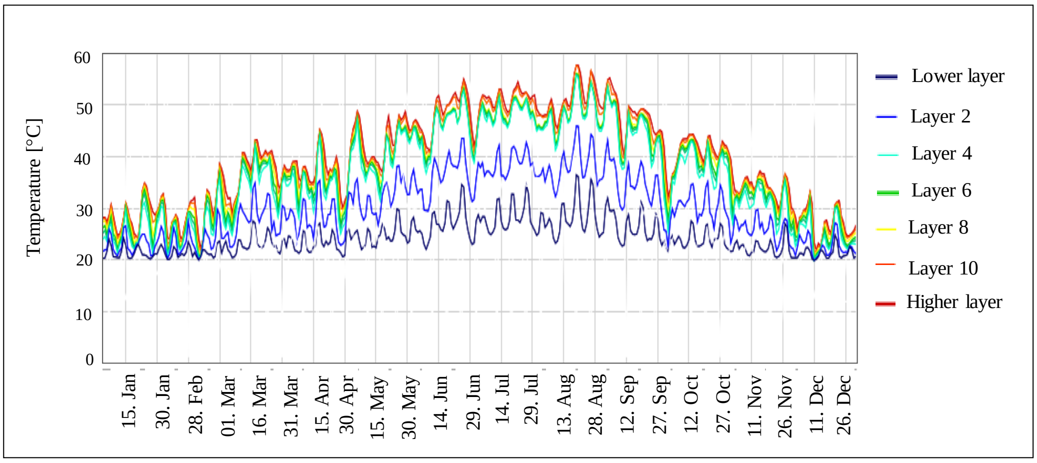


Figure 31: Simulation results for a standard tank (top) and the selected stratified tank (bottom)

The evaluation of the performance of a tank in terms of stratification can be very differently addressed, as analysed in literature (Chandra & Matuska, 2019). In this case, tests aim at analysing the stratification capacity of one tank, with two different characterization approaches and purposes being proposed: (1) characterization of inlet stratification columns, which will focus on analysing the correct inlet process of water flows at different heights depending on their thermal level, and (2) dynamic tests to determine characteristic vertical temperature profiles under different charging conditions (i.e. see 2.2.5).

2.2.4 Operation and validation

The development of the operation and validation phases is basically the same for COOL- and HEAT-LowUP solutions. After the characterization tests, the system will be operated at relevant conditions, in automatic mode, with normal activity in the building. The performance variables that will be recorded during this interval will constitute the reference values to obtain KPIs, which will be used both for the indirect characterization of the subsystems and the validation of models.

The validation tests which will evaluate the accuracy of the TRNSYS models will compare the results between the actual system and the TRNSYS models, to refine the models and try to match real and simulated performances. The outcomes of this validation process will be more accurate representations of the actual system. This process will be periodically repeated to revise the models and adjust potential fluctuations in the actual system, thus ensuring an accurate match of both performances through time. The evaluation of the accuracy of the model will be performed making use of CVRMSE and NMBE, as defined in *ASHRAE Guideline 14-2014* for calibrated models (see section 0). These indexes are based on error measurements, i.e. the difference between simulated results and the actual energy data of the building, and have to result lower or equal to 5% and 15% for hourly calibration and lower or equal to 10% and 30% for monthly calibration, in both cases for NMBE and CVRMSE, respectively.

Due to the complexity of the system, these indexes will be only calculated for selected indicators which characterize each of the subsystems (e.g. PV/T panels, stratified thermal tank, radiant floor). Additionally, the validation of the system performance as a whole will be done through the average indoor temperature in the building and the energy provided by the LowUP system, which will be used as global indicators:

System or subsystem	Indicator description	Symbol	Units
Building (global performance)	Average indoor temperature	T_{indoor}	°C
HEAT-LowUP (integrated system)	Heating power provided by the LowUP system; sum of power delivered by the heat pump, the solar panels and the ECOWEC thermal emulator	P_{cool}	kW
Heat pump	Heating power delivered by the backup heat pump	$P_{therm,HP}$	kW
PV/T-PCM solar panels	Heating power recovered by the PV/T system	$P_{therm,PVT}$	kW
	Electric power produced by the PV/T system	$P_{elec,PVT}$	kW
	Instantaneous thermal performance of the PV/T system	$\eta_{elec,PVT}$	-
	Instantaneous electric performance of the PV/T system	$\eta_{therm,PVT}$	-
Thermal emulator (ECOWEC)	Thermal power delivered by the ECOWEC thermal emulator	$P_{ECO,R}$	kW
Stratified thermal storage tank	Thermal stratification (temperature difference between tank top and bottom)	ΔT_{tank}	kW
Low-temperature radiant floor system	Thermal power delivered by the fluid to the radiant floor	$P_{fluid,RF}$	kW

Table 6: KPI indicators for validation of HEAT-LowUP solution

Any additional indicator will be calculated based on parameters displayed in the table above.

The predictive maintenance strategy will be carried out based on supervisory algorithms that will be obtained from the calibrated models. The actual readings from the system will be compared with the estimated performance resulting from the calibrated models. These differences will contribute to indirectly highlighting potential degradation of components. The quantification of the deviation between actual and expected performance will contribute to the prediction of potential failures, so maintenance tasks to avoid these events will be derived from this process.

2.2.5 *Action Plan*

Procedures and operations included in previous sections will be integrated in an action plan, which will define a logical and systematic sequence for the different tasks to be followed. In spite of including specific timespans for each of the programmed procedures in this action plan, these periods must be considered as illustrative, being susceptible of minor or major modifications depending on the actual development of the activities. For instance, the lack of solar radiation during a prolonged time may entail the adaptation of the characterization test of the solar field.

Commissioning of the subsystems

The commissioning of the different HEAT-LowUP subsystems is expected to take place during first four to seven days. The development of operations included in this phase (see section 2.2.1) is subject to various factors, but the duration would not typically exceed one working day for each of the subsystems if the procedures are methodically followed and no complications occur.

Start-up of the global system

After the individual commissioning of the subsystems, the start-up of the global system will be performed. The first phase will include the operation of HEAT-LowUP system under design, normal and acceptable conditions, as well as the test of all different operation modes. The complete procedure is expected to take one week, although depending on the results of the checking process of the operating modes some extra time may be needed. This set of operations and the commissioning of the subsystems can be carried out at any moment of the year, although design conditions of the system would be preferable.

Characterization of the system

- <u>PV/T Solar field</u>

The PV/T solar field will be tested under different water temperature levels (and different conditions of solar irradiation, if possible).

To that purpose, the solar field will be operated in a specific configuration with a hydraulic bypass over the storage tank and direct energy supply to the auxiliary dry-cooler (implemented as a virtual heat load for characterization tests and scalability analyses)

The heat rejection power of the dry cooler will be modulated in order to control the dry-cooler water outlet temperature (i.e. the collectors' water inlet temperature).

Different water mass flow rates will be tested accounting for the whole operating range of the solar water pump and specifically considering the design mass flow rate (recommended by the manufacturer) as one of the levels to be tested.

<table>
<tr><th>Parameter</th><th>Unit</th><th colspan="12">12 tests (4x3)</th></tr>
<tr><td>Global irradiance on PV/T plane</td><td>W/m²</td><td colspan="12">[Monitored] (both sunny and cloudy days to be chosen for corresponding tests)</td></tr>
<tr><td>PV production</td><td>W</td><td colspan="12">[Monitored after the inverter]</td></tr>
<tr><td>AC Current</td><td>A</td><td colspan="12">[Monitored after the inverter]</td></tr>
<tr><td>AC Voltage</td><td>V</td><td colspan="12">[Monitored after the inverter]</td></tr>
<tr><td>Inlet water temperature</td><td>°C</td><td colspan="3">25</td><td colspan="3">30</td><td colspan="3">35</td><td colspan="3">40</td></tr>
<tr><td>Outlet water temperature</td><td>°C</td><td colspan="12">[Monitored]</td></tr>
<tr><td>Water flowrate</td><td>l/h</td><td colspan="4">800
(*pump at 40%)</td><td colspan="4">1600
(*pump at 70%)</td><td colspan="4">2400
(*pump at 100%)</td></tr>
<tr><td>PV surface temperature</td><td>°C</td><td colspan="12">[Monitored, if possible]</td></tr>
<tr><td>Ambient temperature</td><td>°C</td><td colspan="12">[Monitored]</td></tr>
</table>

Table 7: Monitored parameters for the characterization of the PVT system

- <u>Low-temperature radiant floor</u>

The characterization of the low-temperature radiant floor will mainly consist in a simplified version of the laboratory test performed by the manufacturer to determine the power emission of the actual system in Seville demo site. For this purpose, the CB from COOL-LowUP solution and/or auxiliary air conditioning split units will be used to help reaching constant indoor temperature conditions. Thus, these systems will enable to keep room temperature (T_{room}) at a constant temperature of 20°C.

Water flow rate ($\dot{m}_w$) and inlet water temperature ($T_{w,in}$) will be fixed to constant values for each iteration, and outlet temperature ($T_{w,out}$) will be monitored. Average temperature will be estimated, and power emission will be calculated as follows:

$$\dot{Q}_{rad.floor} = C_{p,w} \cdot \dot{m}_w \cdot \Delta T = C_{p,w} \cdot \dot{m}_w \cdot (T_{w,in-}T_{w,out}) = U \cdot A \cdot \left[\frac{(T_{w,in-}T_{w,out})}{2} - T_{room}\right]$$

For radiant systems ISO 11855 (former ISO 15377) refers to the equation: q = 8.92·(T_{surf}-T_{op}), being these the floor surface and operative temperatures, respectively. Accurate measurement of T_{op} is challenging and normally, it does not provide added value respect to indoor air temperature (except in particular situations with high impact of solarized façades and/or direct incidence of solar radiation). Thus, it has been decided to determine the behavior of a global conductance (U·A) referred to the mean Tw. It is recommended to conduct the tests during the night when control of the boundary conditions is easier (e.g. no uncontrolled, varying internal gains; no influence of solar radiation, etc.)

Three different inlet water temperatures will be tested, and two water flow rates. Moreover, two different room temperature setpoints will be used within the testing programme aiming to characterize the thermal output of the radiant floor system at indoor design conditions as well as at extreme heating needs (representing conditions when the system is turned on early in the morning)

Next, specific values for the characterization tests are included, as well as those variables that need to be monitored or should be fixed:

<table>
<tr><th>Parameter</th><th>Unit</th><th colspan="6">12 tests (2x3x2)</th></tr>
<tr><td>Water flow rate[4]</td><td>l/(h)</td><td colspan="3">2000</td><td colspan="3">2600</td></tr>
<tr><td>Inlet water temperature</td><td>ºC</td><td colspan="2">30</td><td colspan="2">35</td><td colspan="2">40</td></tr>
<tr><td>Outlet water temperature</td><td>ºC</td><td colspan="6">[Monitored]</td></tr>
<tr><td>Floor surface temperature</td><td>ºC</td><td colspan="6">[Monitored]</td></tr>
<tr><td rowspan="2">Room temperature</td><td rowspan="2">ºC</td><td colspan="3">15</td><td colspan="3">21</td></tr>
<tr><td colspan="6">*Temperature to be monitored and maintained with the support of the cooling terminal units</td></tr>
<tr><td>Outdoor air temperature</td><td>ºC</td><td colspan="6">[Monitored]</td></tr>
<tr><td>Global conductance (U·A)</td><td>W/K</td><td colspan="6">[Calculated]</td></tr>
</table>

Table 8: Sequence for the characterization test of the low-temperature radiant floor

Every test will be carried out during six hours or a significant time to ensure that transient conditions are avoided (e.g. the floor is heated, the chilled beams operate properly). Once a test is completed, next tests can be performed. During the data processing, only stable periods for each set of conditions will be used for the obtention of results. Eventually, emitted power (either absolute or divided by effective floor area) will be plotted depending on the difference between room air temperature and average water temperature in the radiant floor.

- <u>Stratification storage tank</u>

The characterization tests will evaluate the stratification capacity of the tank through time with controlled initial conditions. In order to minimize the effect of ambient temperature on the results, tests will be ideally performed during an interval of the day when the variation of ambient temperature is less significant. If this is not possible, adverse effects on the stratification capacity may occur, but the insulation material which covers the tank is expected to minimize these effects.

First, a set of simple experimental **tests to characterize and check the correct behaviour of the inlet stratification columns** are proposed. These tests will start by ensuring a constant and controlled temperature along the whole tank (e.g. temperature difference between top and bottom lower than 2ºC). This condition will be obtained either (i) after natural cooling/discharge of the tank during night, (ii) thanks to heat dissipation in the auxiliary dry cooler, or (iii) thanks to the ECOWEC emulator. In this last case, the emulator will be capable of providing heat at a controlled temperature with flow recirculation from the stratified tank. After a certain time, both tanks will reach a thermal equilibrium, the initial condition will be reached and the test will be able to start.

[4] Water flow rate testing levels have been selected to cover the operating range at Seville demo case based on the possibilities provided by the series water pumps supplying water to the radiant floor system. 2000 l/h corresponds to the design condition.

Once the initial condition is reached, the circulation pump is turned off and the ECOWEC emulator is heated up thanks to the electrical resistance until the upper layer of the emulator tank reaches a given setpoint (which will be the desired water inlet flow temperature for the corresponding test).

Then, the pump is turned on (to provide the design mass flow rate) and hot water from the emulator is transferred to the stratification tank. The inlet is channelled through the inlet stratification column so ideally water will be mixed at the tank layer where the initial temperature is equal to the inlet flow temperature.

The purpose of these tests is, indeed, to characterize the charging process through the stratification column and check that the water inlet flow mixes with the tank water at the expected height. Then, once the pump is turned on, the inlet flow temperature as well as the vertical temperature profile inside the tank will be monitored. Each test will finalize when the inlet water temperature deviates from the expected inlet setpoint or when a volume equal to the emulator tank volume (i.e. 400 l) is injected in the stratification tank.

Secondly, a set of **"dynamic" tests** (aiming to determine a characteristic vertical temperature difference), will be proposed. A fixed flowrate similar to that expected during normal operating conditions will exit the tank trough the bottom port. This flow will be heated up to a given temperature setpoint, and will enter the tank through the stratification column (since inlet temperature will be higher than the initial tank temperature, it is expected that it enters the tank at the upper layers). Three inlet temperature levels and two different initial conditions will be tested. In every case, the test will start with the same conditions inside the tank, i.e. constant water temperature along the height of the volume of the tank. Ideally, the surrounding temperature will be constant and equal for all tests. Each test of the proposed set will be considered as completed once the difference of top and bottom temperatures is lower than 2°C and average temperature remains constant. Top and bottom temperatures in the tank will be monitored through time, as well as ambient temperature.

Depending on the duration of each test, more than one cycle will be performed in a single day. The following table includes all the variables to be monitored, as well as specific values for each of the iterations, and those parameters which should be either fixed or ideally constant.

Parameter	Unit	6 tests (2x3)					
Inlet water flow rate	l/h	[fixed at design values]					
Initial water tank temperature (*homogeneous temp. before test starts)	°C	20			30		
Temperature of water inlet flow	°C	60	50	40	60	50	40
Ambient temperature	°C	[monitored]					

Table 9: Sequence for the 'dynamic' characterization test of the stratification tank

The outcomes of these tests will be several temperature curves (profiles) at different tank layers variating over time. These profiles will be analysed to determine non-dimensional characteristic parameters (focusing on the stratification temperature differences and time delays for temperature dispersion through layers). These parameters will be considered representative of the maximum stratification capacity of the tank for each particular set of conditions.

The figure below represents example theoretical temperature profiles to be obtained at top and bottom layers of the tank during the charging tests (e.g. 50ºC inlet flow, 20ºC initial tank temperature). The time delay and temperature differences in both profiles will allow characterizing the stratification performance of the tank.

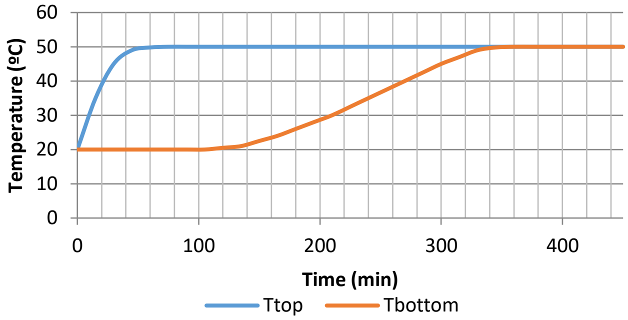


Figure 32. Example theoretical temperature profiles during the stratification tests

In addition, some tests will be conducted in order to characterize the behaviour of the tank in what concerns **heat losses**. To that purpose, the storage tank will be charged to obtain an homogeneous water temperature; then, it free tank temperature evolution will be enabled (i.e. no inlet/outlet water mass flow rates). Such temperature evolution (until the tank thermal condition is close to the equilibrium with the ambient) will be monitored in order to characterize the thermal decay and determine a global heat loss coefficient. Three tests will be conducted considering different initial tank water temperatures. If possible, daytime will be used for the tank charging process and nigh time for the 'discharge'/heat loss characterization.

Parameter	Unit	Test 2.1	Test 2.2	Test 2.3
Inlet water flow rate	l/h	No water inlet/outlet allowed during the test		
Initial water temperature (homogeneous along the tank height)	ºC	80	60	40
Ambient temperature	ºC	[monitored]		

Table 10. Relevant parameters for storage tank heat loss characterization

Operation and validation

In a similar way to what was previously stated for the COOL-LowUP solution, the operation of the system in automatic mode for HEAT-LowUP will start as soon as the previous phases are completed, and should have a minimum duration of one month under winter conditions. The beginning of the validation phase can start after a significant interval of time has been monitored to avoid transient periods related to the start-up.

A week can be considered as a reasonable period for this period, but the decision about the exact moment to start the validation phase will depend on the criteria of the technician in charge of the system. An iterative validation process will allow refining models along with data being recorded. After the operation period is completed, the validation phase may be extended depending on the actual matching process of real and modelled systems.

Next, a Gantt chart summarizes the sequence of main activities included in this action plan:

System	Task/Subtask	Duration	Start	End
Heat LowUP	**2.2.1 Commissioning of each system**	9	1	9
	· Heat pump	1	1	1
	· Stratified tank	2	2	3
	· Radiant floor	2	4	5
	· Solar field	2	6	7
	· Thermal emulator	1	8	8
	· Dry cooler	1	9	9
	2.2.2 Start-up of the global system	3	10	12
	· Start-up phase	3	10	12
	2.2.3 Characterization of the system	28	13	40
	· Stratified tank	14	13	26
	· Radiant floor	7	27	33
	· Solar field	7	34	40
	2.2.4 Operation and validation	62	41	102
	Automatic operation (winter period)	62	41	102
	Validation process	55	48	102

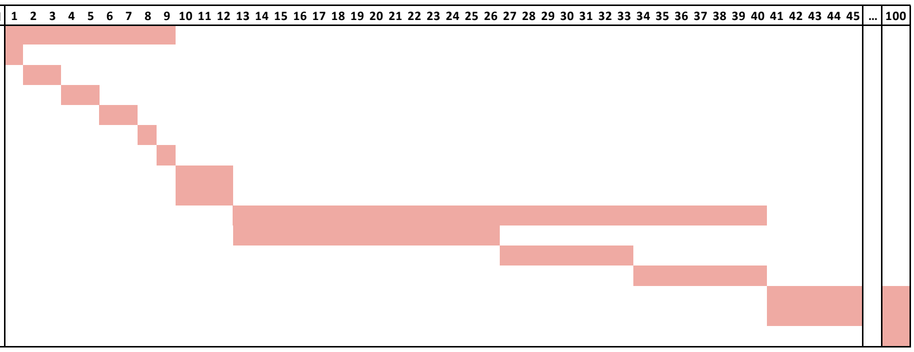


Figure 33. Proposed Gantt for the commissioning, start-up, characterization and operation of COOL-LowUP

Conclusions

An integrated action plan has been preliminarily defined in the present document, which contributes to the management of commissioning, start-up, characterization and validation of the LowUP building solutions and involved subsystems. The systematic definition of the necessary tasks to complete these phases facilitates the coordination of activities required during the delivery of innovative and functionally-tested HVAC systems included within LowUP project. This planning includes the definition of tasks oriented to design review, installation verification, proper system start-ups, functional performance tests, validation of models and a complete documentation of the HVAC systems and the development of the activities themselves.

Due to the particular design conditions of each of the systems, a specific period of the year must be selected for the implementation of the action plan for each of the solutions (HEAT- and COOL-LowUP). Nevertheless, due to the climatic year-to-year modulations, a selected interval for the development of this plan may not correspond with the expected boundary conditions; hence, these periods can be extended and adapted.

Thus, as an initial report, this action plan is subject to be significantly modified during its implementation depending on different aspects (e.g. climatic conditions, actual duration of each phase, potential delays due to malfunctions or failures), which will be completely defined along the development of the plan itself. Therefore, this report is to be considered as a guideline to be adapted and completed during the implementation of the test plan, and a final version containing all the modifications will be submitted to the owner of the facilities.

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