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ECHO

EFFICIENT COMPACT MODULAR THERMAL ENERGY STORAGE SYSTEM

D2.2 – ECHO TES System and Control Concept and Approach

Project information

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Acronyms

BMS - Building Management System

COP - Coefficient of Performance

DHW - Domestic Hot Water

DSC - Differential Scanning Calorimetry

ECHO - Efficient Compact Modular Thermal Energy Storage System

EMS - Energy Management System

ERR - Energy Efficiency Ratio

GHG - Greenhouse Gas

HRU - Heat Recovery Unit

HVAC - Heating, ventilation, and air conditioning system of a building

ICP-OES - Inductively Coupled Plasma Optical Emission Spectroscopy

KPI – Key Performance Indicator

kWh_t - Kilowatt-hour thermal (It is specifically used to quantify thermal energy, differentiating it from kWh from electrical energy)

kWh_e - Kilowatt-hour electric

IKI – Internal Key Indicator

MCHE - Microchannel Heat Exchanger

PCM - Phase Change Materials

PU - Polyurethane

PV - Photovoltaic

PVT - Photovoltaic Thermal

RES - Renewable Energy Sources

SCOP - Seasonal Coefficient of Performance

SEER - Seasonal Energy Efficiency Ratio

TCM - Thermochemical Materials

TES system - Thermal Energy Storage system

TGA - Thermogravimetric Analysis

VCM-s - Conventional single impregnation method

VCM-vac - Vacuum impregnation method

VESD - Volumetric Energy Storage Density

WP - Work Package

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1 Executive Summary

This deliverable D2.2 "ECHO TES System and Control Concept and Approach" comprises all work developed in Task 2.2 - The ECHO TES Concept and Approach, under WP2 of the ECHO project. Task 2.2 aims to develop an innovative and comprehensive approach for Thermal Energy Storage (TES) device design. This includes establishing both quantitative and qualitative Internal Key Indicators (IKIs) for monitoring project progress and objectives, specifically targeting the overcoming of existing barriers. These indicators will be used internally to evaluate the system performance and will have different purpose from the project KPIs defined in deliverable D1.1. It will also involve setting specific parameters related to temperature, heating/cooling demand, and thermal storage density. The task concludes with a preliminary analysis of each demo case requirements, detailing all the necessary sensors, meters, and devices involved in the process.

2 Introduction

2.1 Objectives of the report

The objectives of the report are focused on the development and application of Internal Key Indicators Indicators (IKIs), the analysis of the operational parameters of the TES device, and the preparation for demo case studies.

Chapter 5 aims to define both qualitative and quantitative IKIs essential for monitoring and guiding the project's technical progress. These IKIs are also pivotal for Task T2.5, which involves identifying risks and barriers and conducting the first preliminary analyses.

Another critical objective is the identification and definition of parameters related to the TES device, as outlined in Chapter 6. However, the final design values are currently ongoing, and definitive values are yet to be established. A range of expected values is provided, offering an initial understanding and anticipation of the operational parameters.

Finally, Chapter 7 updates the information on the demo case studies, essential for evaluating the first prototypes of the TES device. While the report provides foundational information, it also notes the absence of detailed sensor equipment specifics for each installation, a section expected to be detailed in the final document.

2.2 Overview of ECHO TES

Energy storage is a fundamental part of the EUs goal to achieve climate neutrality by 2050 and a net-zero greenhouse gas (GHG) emissions economy. Despite the anticipated increase in global energy demand of around 50% in 2030 compared to 2005, the EUs commitment to decrease GHG emissions is driving a significant transformation in energy systems search of a flexible system capable of managing the intermittent nature of renewable energy sources as well as grid electricity production and demand. That capability is present in thermal energy storage (TES) systems, where the electricity load is provided by means of energy conversion and storage.

ECHO goal is to develop a Plug&Play, complete, sustainable, flexible, modular, digitally controlled and competitive system exploiting thermal energy storage (see Figure 1). This compact and smart TES solution will be based on the use and optimization of thermochemical materials (TCMs), combined with phase change materials (PCMs), for space heating, cooling, and domestic hot water (DHW) production and, optionally, with ice storage for large cooling needs. The ambition of the project is to achieve a power rate not less than 5 kW for charging 1 m^3 of TCMs reactor with a temperature around 80-90 °C provided by an internal heat pump.

In order to achieve these objectives, the system will be based on the energy storage capacity and inherent heat pumping potential of thermochemical materials (TCMs), but unlike the already developed TCM solutions, the system will have an innovative configuration based on a novel thermodynamic cycle that is able to maximize the reaction rate and charging/discharging power.

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Also, the proposed solution will include a closed TCM reactor where TCMs have been chosen for high reaction heat, good reversibility and fast charging and discharging rates. Additionally, PCMs will be in charge of the insulation of the system, being capable of maintaining the operating temperature high enough to exploit the discharging/charging reaction with the highest efficiency.

One of the most important aspects of this solution is that ECHO device can be adapted to the end-user's needs in terms of charging and discharging power, dimensions and types of energy sources. This flexibility can be achieved by changing parameters such as the size of the reactor and the amount of TCMs. As for the energy source, there are two options. The first one is charging the device directly by means of an internal heat pump, using the electricity overproduction from the grid or from renewable sources.

The control system developed in the project will help to accomplish this property by operating the building integrated energy system with local energy production and storage assets, adjustable loads, and bi-directional interaction with the power grid.

Compactness, cost-effectiveness, and sustainability will be a big concern in the ECHO solution design, too. Compactness and cost-effectiveness will be achieved with the TCM design, through a proper selection and adaptation of heat exchangers with an even distribution of minimum number of working fluids (air and water or water-glycol).

Furthermore, sustainability will be ensured by designing the heat pump to maximize its efficiency and minimize GHG emissions, and making sure that the reactions in the TCMs reactor produce stable reaction products that are not explosive, flammable, or toxic.

Finally, the control system will also contribute to making the ECHO TES solution more sustainable and cheaper, as it can take advantage of low grid electricity prices to replenish storage, as well as making the most of available local PV and PVT panels.

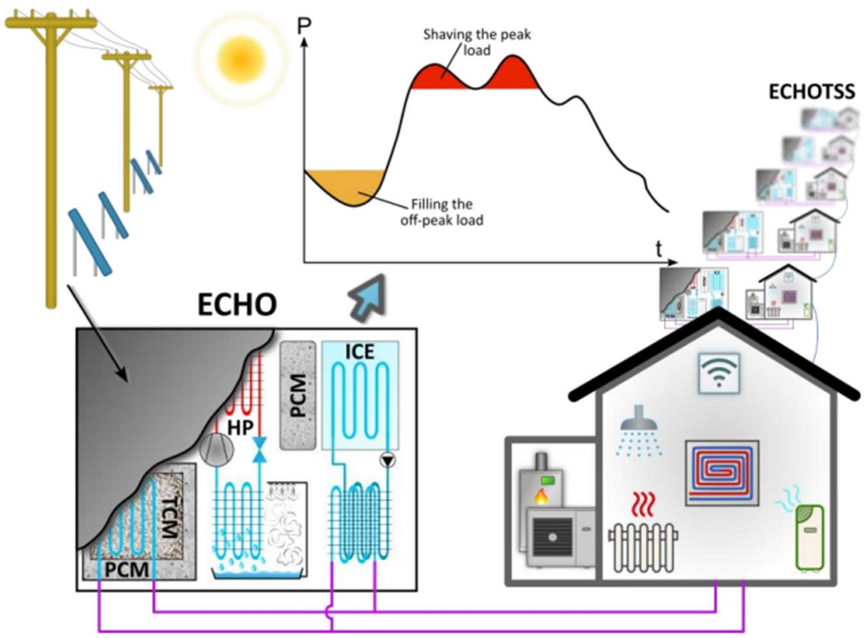


Figure 1. ECHO project

3 Theoretical Framework

3.1 Concept of Thermal Energy Storage (TES)

The TES system will be designed as a closed-loop type, enabling more precise management of the reactor temperature to better meet the demand for space heating/cooling and DHW production (see Figure 2).

The adaptability of this solution to the buildings will be guaranteed by directly connecting the system to the hydronic loop of existing heating and cooling systems in a simple manner. Moreover, using a heat pump to convert electricity into heat directly for TES enables the developed TES to become a simple Plug&Play solution.

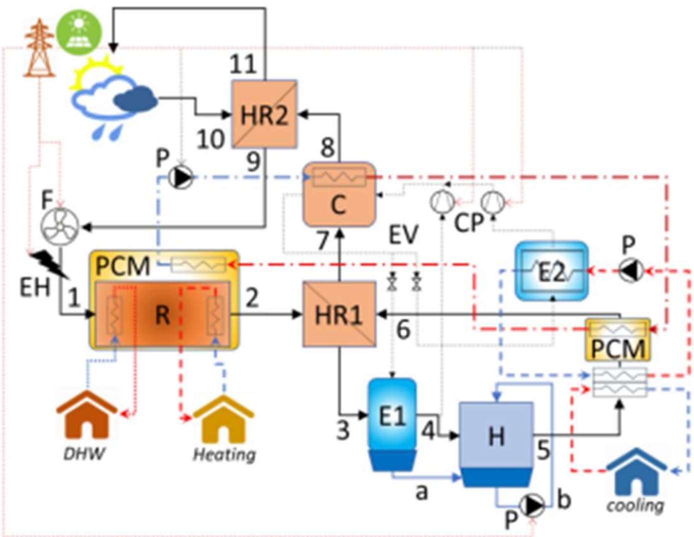
Its design allows to operate in four different modes:

1. Heating mode: for space heating and DHW through the utilization of the thermal energy released by TCMs.
2. Charging mode: thermal energy storage obtained through TCMs dehydration.
3. Cooling mode: research is currently underway to meet the energy demand for space cooling and domestic hot water simultaneously through TCMs hydration.
4. Super-cooling mode: optimal configuration of the system that enables the fulfilment of a significant cooling energy demand. A cold storage system is added to the main TES system.

The required flexibility to meet energy demand and supply needs is attained by managing the air flow rate, relative humidity entering the reactor, and heat exchange conducted by the heat recovery units. A dedicated control system will monitor all these parameters.

PCMs will be used to achieve various objectives, including insulations of the TCM reactor and the cooling unit, and compensation of the energy demand in humidification.

The first objective will be achieved by coating the TCM reactor with PU insulations containing specific PCMs, enabling quicker discharging cycles due to the slower cooling of the reactor, resulting in greater operational flexibility. A similar solution will be adopted for the second purpose, with a melting point tuned for cooling storage. The third feature will be performed by a PCM buffer tank, which will solve the problem of relying on an energy source for water evaporation.



Name	Description
C	Condenser
CP	ComPressor
E1	Evaporator
E2	Evaporator low temp. (optional)
EH	Electric Heater
EV	Expansion Valve
H	Humidifier
HR	Heat Recovery unit
DH	DeHeater unit
R	TCM Reactor
PCM	Phase Change Material
P	Pump
F	Fan
	Hydronic loop (heating/cooling)
	Hydronic loop (DHW)
	Hydronic loop (PCM)
	Power
	Air duct
a	Condensed vapour
b	Pressurised water

Figure 2. Schematic of the TES solution

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3.2 Importance in Residential Energy Management

Electricity consumption in the residential sector covers a 55% share at global level. The EU Energy Policies are driving a reduction of GHG emissions to achieve a climate-neutral economy by 2050. To achieve this goal, various actions were considered, related to the increase of both energy efficiency and renewable energy production in this sector.

ECHO TES device is a great solution to achieve this goal due to its flexibility. Indeed, it can be sized according to the demand profile of the building (single house, terrace house, multi-apartment building), the supply profile of the renewable energy sources and the available space. For example, a unit with a reactor of 200-300 kg of salt hydrates provides sufficient storage capacity for a renovated or newly built house or an apartment of about 150 m^2 in most of the European climate zones. In addition, it is possible to install several modules in parallel to serve larger buildings or heating/cooling networks.

Moreover, the ECHO TES will also be able to take advantage of low electricity prices of the grid through its advanced control system and replenish storage next to making maximum use of local PV and PVT panels.

Through its PCM enhanced insulation, the ECHO TES minimizes storage losses from the reactor. In combination with the closed loop concept, the TES can operate constantly at temperatures of 60°C. It also connects directly to the heating and DHW systems to avoid expensive investments in replacing distribution systems and terminals in buildings renovations.

In conclusion, after having seen the various advantages offered by the ECHO solution, it can be stated that it will have a significant effect on residential energy management due to its flexibility, which allows it to be used in a wide variety of cases, and thanks to its cost-effectiveness and sustainability, increasing efficiency and the use of renewable energy sources for heating, cooling and domestic hot water.

4 Holistic approach ECHO TES System Design

4.1 Overview of System Components

The main components of the ECHO TES system are:

- The TCM reactor;
- The humidifier;
- The heat recovery unit;
- A heat pump;
- PCM thermal storage, and;
- Cold accumulator

4.1.1 TCM Reactor

The TCM reactor is the main component of the system, containing the TCM material in its matrix. In the current design phase, it is assumed that the heat demanded by the user in the heating phase is extracted using two heat exchangers, one located “inside” the reactor and one at the exit, which exchanges sensible heat with the exiting air. However, the choice of only one heat exchanger at the exit is under definition, too. This component is involved in all the operation modes of the system: heating, recharge, cooling and ice formation.

The system is well insulated to keep the operating temperature at a high level to better exploit the charge and discharge reaction. The reactor’s thermal insulation should be made using a combination of conventional and less conventional materials, the first being polyurethane (PU) rigid foam composites and the latter being PU with PCMs. By employing PCMs, the insulation layer will have a thermal buffer effect that works at the phase-change temperature of the chosen PCM. A divergent section is considered at the entrance of the reactor to lower the airflow velocity and to distribute the air and moisture better. The airflow velocity range for this application ranges from 0.01 to 0.04 m/s.

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From the first laboratory tests, it is observed that the temperature lift in the reactor is 8÷12°C. This limitation is important as it binds the conditions of power produced and extracted.

The reactor should also be equipped with filters at the outlet to avoid the possibility that salt particles that might detach from the matrix due to repeated cycles or degradation reach the other components of the system such as the humidifier, which impurities could damage. The filters present additional pressure drops that the fan must overcome to provide the correct flow rate to the reactor.

Pressure losses inside the reactor are unknown at this stage because they depend on the design of the reactor and require laboratory measurements on the real physical prototype after its construction.

4.1.2 Humidifier

The humidifier is a crucial component for a TES closed system with TCM since the airflow is not renewed: the moisture content of the air is reduced in the reactor during the heating phase and increased during the recharging phase. The humidifier is required only during the heating phase and the free-cooling phase because its purpose is to reintegrate the adsorbed water into the airflow.

The choice of the humidifier greatly impacts the system and the sizing of the other components. The adiabatic ultrasonic humidifier was chosen because of its limited space requirements and low electrical energy demand.

The ultrasonic humidifier technology is based on the electric stimulation of an ultrasonic piezoceramic transducer to generate oscillations, producing ultrasonic vibrations, and generating aerosol in the water tank above the transducers themselves. The aerosol mist generated is then incorporated by the airflow.

4.1.3 Heat recovery unit

The heat recovery unit (HRU) plays a crucial role in the thermodynamic cycle by lowering the temperature of the airflow leaving the TCM reactor and preheating it post-cooling in the evaporator or condenser. This cooling is essential for regulating the humidifier's humidification rate during heating and free-cooling stages. It also reduces the energy needed for air moisture condensation in recharge and ice formation phases.

4.1.4 Heat pump

The ECHO module is coupled with a novel heat pump during the recharge and ice-formation phases to help with the required cooling production. The cold production is used in the recharge phase to dehumidify the airflow and in the ice-formation phase to produce ice in the external cold tank.

The working fluid is R515B (an azeotropic mixture formed by R1234ze and R227ea with low GWP). Based on the latest available data on the reactor's design, the most suitable configuration for the heat pump seems to be a water-glycolate – water heat pump. The evaporator and the condenser are plate heat exchangers. In case of new data, or new investigations or considerations, the configuration can be varied.

The water/glycol - water HP is motivated by:

- Possibility of more precise modulation of the cycle.
- Possibility of working at partial load: if the power request is lower than the one corresponding to the minimum rotational speed of the compressor, the unit must be stopped in case of HP operating at direct expansion or condensation. Vice versa, with water coil a power modulation might be implemented by means of a pump coupled with a tank.
- Possibility of more precise measurements and data collection.
- Easier maintenance.
- More reliability.
- Since the efficiency of the system is greatly dependent by the condition of air entering in the reactor, the reduction of efficiency due to the double heat exchange is negligible.

All the points have more consistence since considering the first design of the prototype.

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4.1.5 PCM Thermal Storage

The PCM thermal storage is required by the system to preheat the airflow after the adiabatic dehumidification before entering the recuperator and is requested to supply non-negligible amounts of heat during the heating phase.

From the first ideal heating phase model, the power supplied by the PCM tank during operation is in the range of 1-1.2 kW_t. For this reason, the choice of the correct PCM is crucial.

The required phase-change temperature of the PCM material should be around 27-35°C to have high storage efficiency thanks to a reduced temperature difference with the ambient air.

4.1.6 Cold accumulator

In the super-cooling mode, a cold accumulator filled with water-ethanol glycol and encapsulated eutectics (melting point around -3°C) will be charged by the heat pump operating as chiller. This auxiliary part will be optional and will be able to store 3 kW_t for 3 h at -3°C. The cold accumulator will be insulated by PU and PU with PCM (with melting point at ambient temperature).

4.2 Thermal Energy Storage Mechanisms

The main component of the system is the TCM reactor, which is used for the purposes described in the previous section. Here, the most significant TES mechanisms are carried out by TCM. However, also PCMs play a pivotal role in the TES mechanisms of the system.

The design of the TES allows to operate in four different modes, which strictly depends on the operation conditions in which the TES finds itself in operation. For example, the system could be sometimes thermochemically charged and potentially available, but its use may not be necessary given the availability of other free renewable energy sources. Similarly, the prolonged absence of low-cost or free energy sources does not allow the system to carry out adequate charging cycles, which can therefore make it unusable. In this case, the operation of the system is highly dependent on the energy market, climate-related conditions and thermal load profile on the user side.

Taking into consideration TCM, TES mechanisms are carried out through hydration and dehydration of the material. The former allows TCM to provide thermal power for space heating and potentially cooling, as well as for DHW production and preheating**,** while the latter is destined for the regeneration of the TES system. For the purposes of the TES system, a reversible vapour compressed refrigeration cycle (the heat pump above mentioned) is used. When it is used as heat pump, its operation fulfils the function of dehumidifier and heater of the air stream, whilst in the other condition it is potentially used as chiller serving the cooling storage operation and charging the cold accumulator.

In detail, the TES system uses the following two configurations during the heating period: use and regeneration of the TES. Hydration occurs when the use of the TES is required. The humid air flows through the reactor and TCM adsorbs moisture from it. An exothermic reaction occurs at about 60°C. TCM discharges the stored thermal power to the airflow and increases the air temperature; thus, the air exchanges thermal energy with the heat carrier fluid of the heating plant. In fact, if the system is in heating period, the thermal power released to the air is exploited through the water-based heat exchanger to provide space heating (required supply water temperature <50°C), produce or preheat DHW or for thermally regenerating the airflow entering the reactor (to increase the temperature level of the TCM if necessary). The reaction can be maintained isothermal by regulating the air flow rate and/or the humidity.

In cooling period, the thermal power released by TCM after its hydration is exploited to meet DHW demand and to thermally regenerate the air entering the condenser. Then, due to the reintegration of humidity, temperature of the airflow decreases up to 8-10°C, thus presumably providing suitable supply water temperature for space cooling. In this way, humidification is managed to achieve a suitable temperature for air conditioning needs, by adopting the cooling tower process. At the same time, the refrigeration cycle can

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be used for cooling and storage at lower temperature level compared to the temperatures obtained from the evaporation cooling process.

Whilst hydration causes the discharging of the TES system, dehydration is aimed at its regeneration. When free electricity (e.g. from PV systems) or low-cost electricity (from the grid) is available, the inverse cycle at the condenser side overheats the air flow and thermally reintegrates PCMs. The air flow is firstly dehumidified by the evaporator, which removes the water vapour previously released from the TCM during the flowing across the TCM bed, and then it exchanges heat with the condenser. Then, again, the dry and overheated air is sent to the TCM reactor, where it is humidified again by TCM thanks to the release of the water previously adsorbed during the discharging process.

Considering PCMs, TES mechanisms are aimed at three different objectives:

- to speed up TCM discharging: suitable PCMs are adopted to be put inside the PU insulation as coating of TCM reactor, destined to accelerate discharging cycles due to the slower cooling of the reactor, thus resulting in greater operational flexibility.
- to insulate the cooling unit (optional): PCMs in PU insulation with a melting temperature appropriate for cooling storage are used.
- to compensate the energy demand for humidification: a thermal storage tank integrated with PCM is implemented in the system to provide an energy source for vapour production necessary for TCM discharging. The PCM tank operates at a temperature easy to be maintained and is recharged by the HP condenser during the charging phase.
- to store cold in the cold accumulator in form of eutectics, with melting point around -3°C.

4.3 Control and Management System

In pursuit of the automated operation of the ECHO system, a comprehensive control and management system has been designed within the framework of WP5 and is presented in the Figure 3. The lowest layer of control strategy covers direct asset control which is executed through purposefully engineered hardware and software units. These units integrate with the ECHO TSS system and existing Building Management System (BMS) / Energy Management System (EMS) via standardized protocols. This integration facilitates the adept control of diverse assets present at the pilot sites, including but not limited to heat pumps and thermal energy storage systems.

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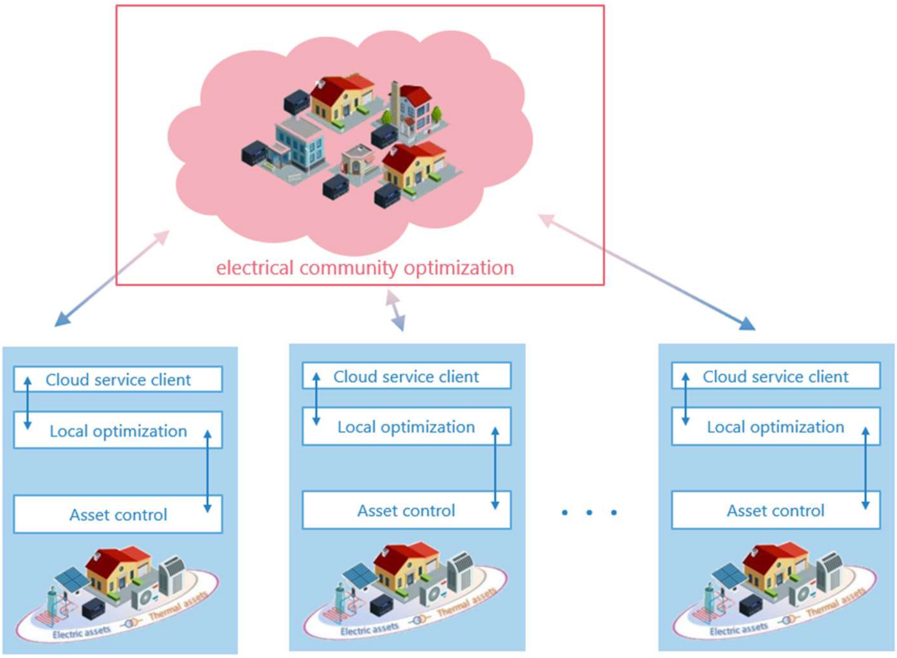

Figure 3. Scheme of the control system

Next level and mid-level control strategy comprise a data-driven control algorithm distinguished by a reinforcement learning approach. This algorithm is strategically deployed locally within the control cubicle, engendering an artificial intelligence (AI)-based control framework. The envisioned outcome of this approach is the formulation of an optimal asset schedule; such schedule is subsequently harnessed by direct asset control algorithms. This schedule aligns itself with the demand profile, provided from cloud-based high-level optimization utilizing a reinforcement control strategy. AI-based service responsible for this optimization will undergo training based on the ECHO TSS models, developed within the frame of WP4.

Finally, the highest level of the control hierarchy is the cloud-based service, specifically dedicated to neighbourhood-level optimization. This service considers various factors, including grid state, available RES, anticipated thermal and electrical loads, and, most importantly, market prices. This analytical service results in the provision of an optimal demand profile on the household level which is further translated into individualized recommendations and control actions through the intermediary and low-level control strategies.

5 Internal Key Indicators

This section presents a comprehensive representation of a TES system through a selection of key indicators. The purpose of this selection is to assess the TES system performance and track the project objectives attainment. KPIs are critical tools used to monitor and assess the progress and effectiveness of a project. They provide measurable values that reflect the success or failure of a project in reaching its objectives.

Firstly, it is important to make the following distinction: throughout the entire project execution, we utilize project KPIs to monitor the evolution and development of the project. These KPIs are specifically evaluated during the execution of Task T1.1. They serve as a continuous metric to gauge the project's progression and to ensure alignment with the main project objectives.

However, the objective of this task (Task T2.2) is to develop a set of internal key indicators that will be employed across the main phases of the project. These phases include simulations, experimental tests, and the evaluation of the demo sites. The development of these indicators is crucial as they are designed to provide a comprehensive overview of the project's performance across its different stages (see Figure 4).

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In essence, while project KPIs are utilized throughout the project lifecycle to monitor its ongoing status, the focus of this task is to establish a set of specific and specialized indicators. These specialized indicators are tailored to assess the critical aspects of the project's main phases, offering insights that are pivotal for decision-making and for enhancing the project's outcomes.

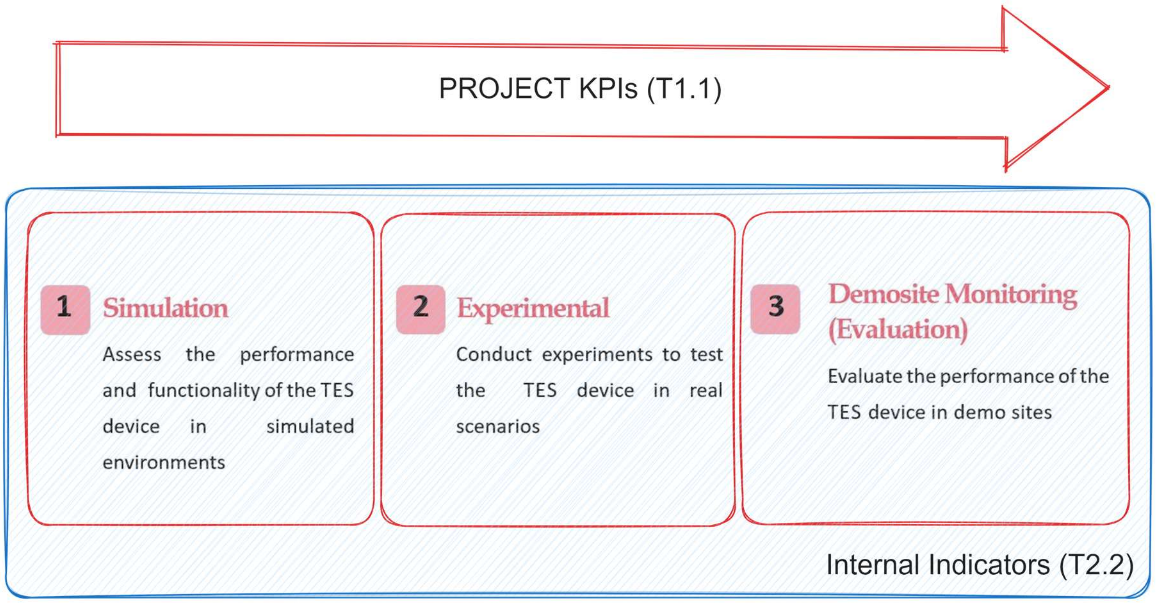

Figure 4. Project KPIs (T1.1) vs Internal indicators (T2.2)

The internal indicators developed in this task have been grouped into two categories: quantitative and qualitative. Each category is divided into four sections, focusing on electricity grid, energy, social/environmental field, and market/regulation sector (see Figure 5 and Figure 6).

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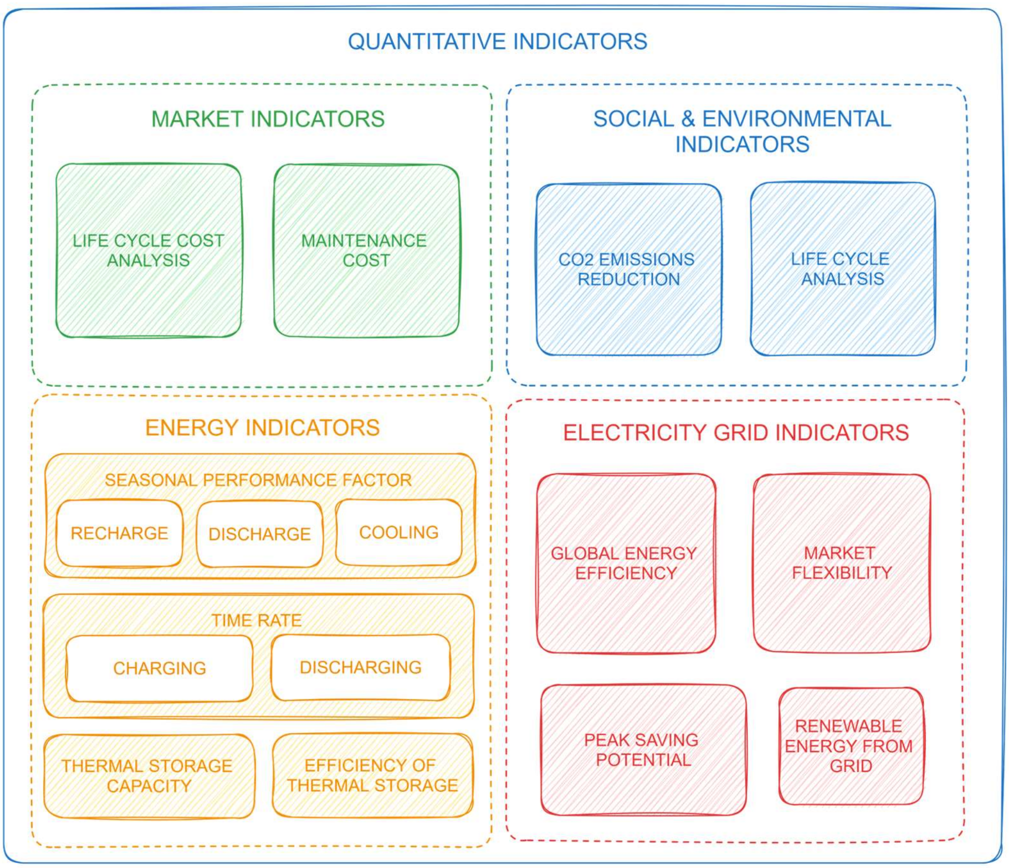

Figure 5. Quantitative Indicators

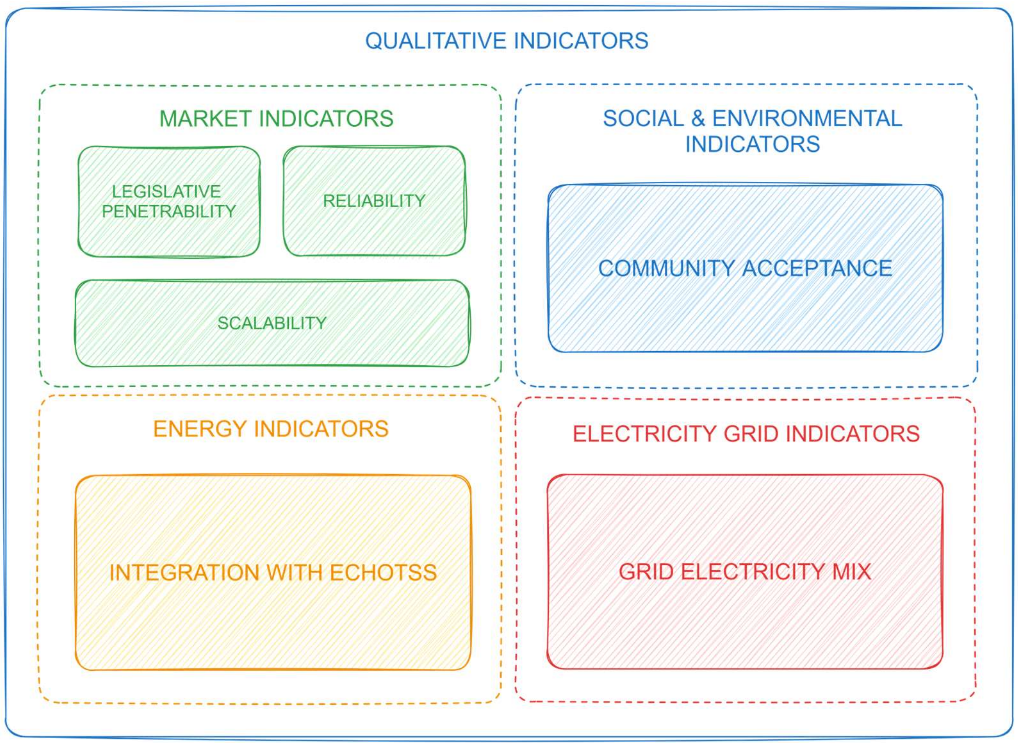

Figure 6. Qualitative indicators

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A detailed exposition of the identified indicators is provided below. A thorough definition of the indicators is fundamentally crucial to ensure their successful evaluation subsequently. Clarity and details in the description of each indicator are imperative to grasp their significance and impact, thereby enabling an accurate and effective evaluation. To systematically present this vital information, a table has been constructed for each indicator comprising the following fields:

1. **Indicator**: This lists the name of the indicator (including code), offering a quick reference to the specific parameter under evaluation.
2. **Description**: Here, a detailed explanation of what each indicator measures and represents within the context of the project is provided, ensuring a comprehensive understanding of its relevance and scope.
3. **Units**: This section specifies the units of measurement for each indicator, which is crucial for the interpretation of data and ensuring consistency in the evaluation process.
4. **Equation**: If applicable, the equation used to calculate unequivocally the indicator is presented here, providing a mathematical basis for its quantification.
5. **Nomenclature**: This part delineates the symbols and terms used within the equation or description, ensuring clarity in communication and understanding of the indicators.
6. **How is going to be measured?**: This field explains the methodology or the tools that will be employed to measure each indicator, outlining the approach to data collection and analysis.
7. **Phase of the project**: This section identifies the specific phase of the project during which the indicator will be evaluated.
8. **Evaluation**: Here, the criteria or benchmarks for evaluating the indicator are defined, providing a framework for assessing whether the project outcomes align with the set objectives. It is also indicated in which project deliverable the indicator will be evaluated.
9. **Limitations and assumptions (if needed)**: If there are any limitations or assumptions associated with the indicator, they are documented in this column, providing context and acknowledging potential constraints in the evaluation process.

5.1 Quantitative Indicators

5.1.1 Electricity grid indicators

The category of electricity grid indicators holds great importance in assessing and improving the efficiency of energy systems. It serves as a critical framework for evaluating the performance and sustainability of electrical power networks. The list of the indicators that are included in this category is as follows:

QTI1.1: GLOBAL ENERGY EFFICIENCY	
Units	Percentage (%)
Equation	$Global\ Energy\ Efficiency\ (\%) = \left(\frac{Total\ Thermal\ Energy\ provided\ by\ TES\ System}{Total\ Electricity\ Consumed}\right) \times 100$
Nomenclature	$Total\ Thermal\ Energy\ provided\ by\ TES\ System =$ during a selected time interval, the total amount of thermal energy (cooling/heating) that is successfully provided to the building from the TES system. $Total\ Electricity\ Consumed$ = The total amount of electrical energy consumed by the TES system during this selected time interval.

How is going to be measured?	The measurement will involve quantifying the thermal energy from the TES system to the building and the electricity consumed during the process, applying the defined equation to calculate the efficiency percentage.
Phase of the project	This indicator will be evaluated at demosite evaluation (WP6)
Evaluation	The efficiency improvement will be evaluated by comparing the calculated energy efficiency of the TES system with the efficiency of conventional systems. This indicator will be evaluated in deliverables D6.1, D6.2 and D6.3.
Limitations and assumptions (if needed)	This indicator provides a gross measure, considering the total thermal energy supplied and the total electrical energy consumed, without distinguishing between energy used in different stages or processes within the TES system.

QTI1.2: MARKET FLEXIBILITY (MFI)	
Description	Measures the system's ability to adapt to market price fluctuations by optimizing energy purchases.
Units	Percentage (%)
Equation	$$MFI = \frac{\mathrm{EI}_{\mathrm{HP}} - \mathrm{EI}_{\mathrm{LP}}}{\mathrm{EI}_{\mathrm{HP}} + \mathrm{EI}_{\mathrm{LP}}} \times 100$$
Nomenclature	EI_{HP} = Energy purchased at the hour with the highest price. EI_{LP} = Energy purchased at the hour with the lowest price.
How is going to be measured?	*Using the electricity grid model, data will be analysed to identify power purchase patterns. The EI_{HP} and EI_{LP} will be calculated for different periods, considering price fluctuations and the system's response to them.*
Phase of the project	T2.4 - Simulation (electric grid)
Evaluation	The results will be interpreted to assess the system's ability to adapt to market fluctuations in the Deliverable D2.4 of the project. A range of desirable flexibility will be considered, and recommendations to increase market flexibility if necessary. Possible values for this factor are: MFI>0: A potential to shift power from the peak to the valley exist, being higher as PSP (see below) is higher. MFI=0: There is not market flexibility (flat price) MFI<0: The consumer is already exploiting its flexibility, as energy purchased at low price is already higher than purchases at high price.

QTI1.3: PEAK SAVING POTENTIAL (PSP)	
Description	It measures the relation between the mean power demand during the peak period and the mean power demand during the valley period.
Units	Per unit (pu)
Equation	$$PSP = \frac{Eh_{peak}}{Eh_{valley}} - 1$$
Nomenclature	Eh_{peak}: Electricity consumed during the hour of maximum consumption (kWh) during a typical day. It is equivalent to the mean power demand during that hour.

	EhEh_{valley}: Electricity consumed during the hour of minimum consumption (kWh) during the same typical day as considered for the evaluation of Eh_{peak}. It is equivalent to the mean power demand during that hour.
How is going to be measured?	The energy consumption in both periods is obtained from the measurements provided by the distributor. This factor could be evaluated for the whole grid or just for a specific area (one or several substations).
Phase of the project	T2.4 - Simulation (electric grid).
Evaluation	The value will be evaluated in Deliverable D2.4, measuring the potential of reducing the peak demand during a typical day. Typical days will cluster similar patterns of consumption according to specific characteristics (seasonality, work life, etc.) and must be identified in advance. Possible values for this factor are: PSP>0: A potential to shift power from the peak to the valley exist, being higher as PSP is higher. PSP=0: There is not saving potential (flat load curve) PSP<0: There is not saving potential (demand is higher during the valley)

	QTI1.4: RENEWABLE ENERGY FROM GRID (REG)
Description	It measures the relation between the potential to produce the maximum capacity of renewable energy for a specific period of time (e.g. one hour) and the available capacity to store such energy in storage devices
Units	Percentage (%)
Equation	$REG = \frac{ER_{cap} - ER_{gen}}{STOR_{cap}} \cdot 100$
Nomenclature	ER_{cap} is the maximum capacity to produce renewable energy for a specific period (e.g. one hour). ER_{gen} is the amount of electric energy produced by renewable energy sources and supplied to the grid during the aforementioned period. $STOR_{cap}$ is the available capacity to store energy in the ECHO TES devices installed in the considered grid, for the same period.
How is going to be measured?	ER_{cap} is evaluated by modelling (e.g. PVSyst), according to the characteristics of production devices and actual availability of natural resources (e.g. solar radiation). ER_{gen} is obtained by measurement performed by the distribution company. $STOR_{cap}$ is obtained by modelling, according to the information available to the distribution company with tools developed during the project ECHO
Phase of the project	T2.4 - Simulation (electric grid)
Evaluation	The results will be interpreted in the Deliverable D2.4 of the project. Possible values for this factor are: REG>100%: The capacity to store energy is lower than the maximum amount of extra renewable energy that could be produced. REG=100%: The additional capacity to produce the maximum possible renewable energy in one period is equal to the capacity which may be stored

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	REG<100%: The capacity to store energy is higher than the maximum amount of extra renewable energy to be produced. REG=0: The total production of renewable energy is delivered to the grid, so that there are not excesses of energy to be stored.

5.1.2 Energy indicators

These indicators provide valuable insights into the capability, effectiveness, and productivity of the energy storage and utilisation across various applications. Evaluating energy indicators is crucial for measuring the system ability to store and deliver thermal energy efficiently, optimize the performance of heat pumps, and assess overall energy consumption patterns. The list of the indicators that are included in this category and how they are calculated is as follows:

QTI2.1.1: SEASONAL PERFORMANCE FACTOR – RECHARGE MODE (SPF_R)	
Description	Measures the system's seasonal performance during the recharge mode (see Figure 7).
Units	no units (kWh_t/kWh_e)
Equation	$SPF_R = \frac{E_{th,\,user} + E_{th,\,airloop} + E_{th,\,disch}}{E_{el,\,hp} + E_{el,\,wloop} + E_{el,\,aloop} + E_{el,\,user} + E_{el,\,dryCooler}}$
Nomenclature	$E_{th,\,user}$= Thermal Energy delivered to the user $E_{th,\,airloop}$= Net Thermal Energy exchanged between the water loop and the air loop $E_{th,\,disch}$= Thermal Energy discharged to outdoor (negative contribution) $E_{el,\,hp}$= Electrical Energy absorbed by the heat pump (compressor, valves) $E_{el,\,wloop}$= Electrical energy absorbed by the water loop (circulators) $E_{el,\,aloop}$= Electrical energy absorbed by the air loop (fan) $E_{el,\,user}$= Electrical energy absorbed by the user (circulator and fan) $E_{el,\,dryCooler}$= Electrical energy absorbed by the dry cooler (fan)
How is going to be measured?	Using energy meters for thermal energy and electrical energy meters for electrical energy.
Phase of the project	Experimental (WP4) and demosite evaluation (WP6).
Evaluation	The results will be interpreted to assess the performance of the system during the recharge mode, and should be monitored, and later compared with, in demo cases applications. This indicator will be evaluated in deliverables D4.3, D6.1, D6.2 and D6.3.
Limitations and assumptions	Accuracy of instruments must be considered.

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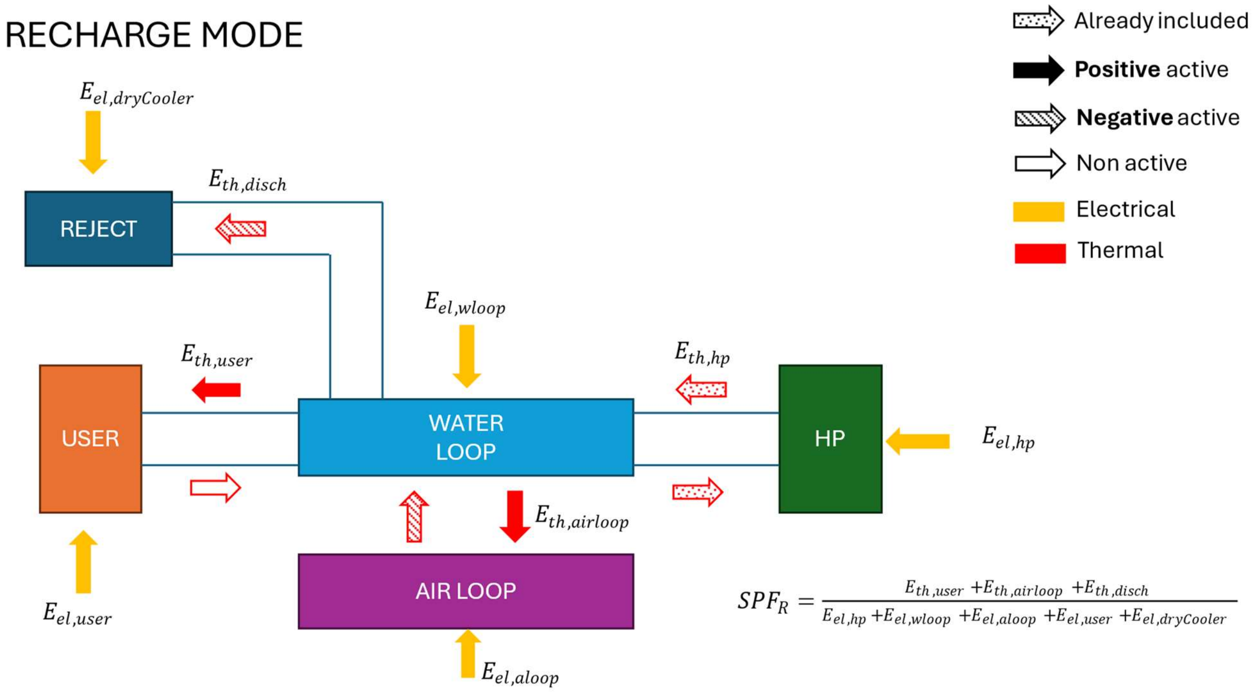

Figure 7. TES device operating in recharge mode

QTI2.1.2: SEASONAL PERFORMANCE FACTOR – DISCHARGE MODE (SPF_D)	
Description	Measures the system's seasonal performance during the discharge mode (see Figure 8)
Units	no units (kWh_t/kWh_e)
Equation	$SPF_D = \frac{E_{th,\,user}}{E_{el,\,wloop} + E_{el,\,aloop} + E_{el,\,user}}$
Nomenclature	$E_{th,\,user}$= Thermal Energy delivered to the user $E_{el,\,wloop}$= Electrical energy absorbed by the water loop (circulators) $E_{el,\,aloop}$= Electrical energy absorbed by the air loop (fan, humidifier) $E_{el,\,user}$= Electrical energy absorbed by the user (circulator and fan)
How is going to be measured?	*Using energy meters for thermal energy and electrical energy meters for electrical energy*
Phase of the project	Experimental (WP4) and demosite evaluation (WP6)
Evaluation	The results will be interpreted to assess the performance of the system during the discharge mode, and should be monitored, and later compared with, in demo cases applications. This indicator will be evaluated in deliverables D4.3, D6.1, D6.2 and D6.3.
Limitations and assumptions	Accuracy of instruments must be considered

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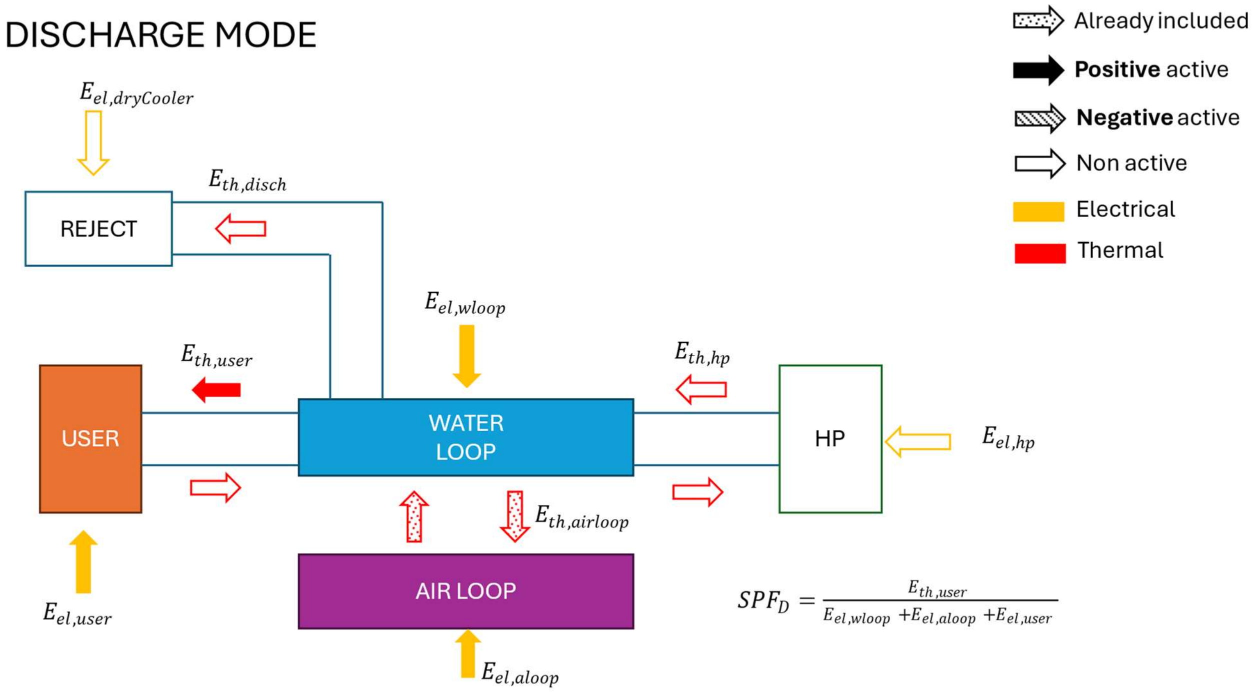

Figure 8. TES device operating in discharge mode

QTI2.1.3: SEASONAL PERFORMANCE FACTOR – COOLING MODE (SPF_C)	
Description	Measures the system's seasonal performance during the cooling mode (see Figure 9)
Units	no units (kWh_t/kWh_e)
Equation	$$SPF_C = \frac{E_{th,\,user} + E_{th,\,disch}}{E_{el,\,hp} + E_{el,\,wloop} + E_{el,\,user} + E_{el,\,dryCooler}}$$
Nomenclature	$E_{th,\,user}$= Thermal Energy delivered to the user for domestic hot water production and extracted for space cooling $E_{th,\,disch}$= Thermal Energy discharged to outdoor (negative contribution) $E_{el,\,hp}$= Electrical Energy absorbed by the heat pump (compressor, valves) $E_{el,\,wloop}$= Electrical energy absorbed by the water loop (circulators) $E_{el,\,user}$= Electrical energy absorbed by the user (circulator and fan) $E_{el,\,dryCooler}$= Electrical energy absorbed by the dry cooler (fan)
How is going to be measured?	*Using energy meters for thermal energy and electrical energy meters for electrical energy*
Phase of the project	Experimental (WP4) and demosite evaluation (WP6)
Evaluation	The results will be interpreted to assess the performance of the system during the cooling mode, and should be monitored, and later compared with, in demo cases applications. This indicator will be evaluated in deliverables D4.3, D6.1, D6.2 and D6.3.
Limitations and assumptions	Accuracy of instruments must be considered

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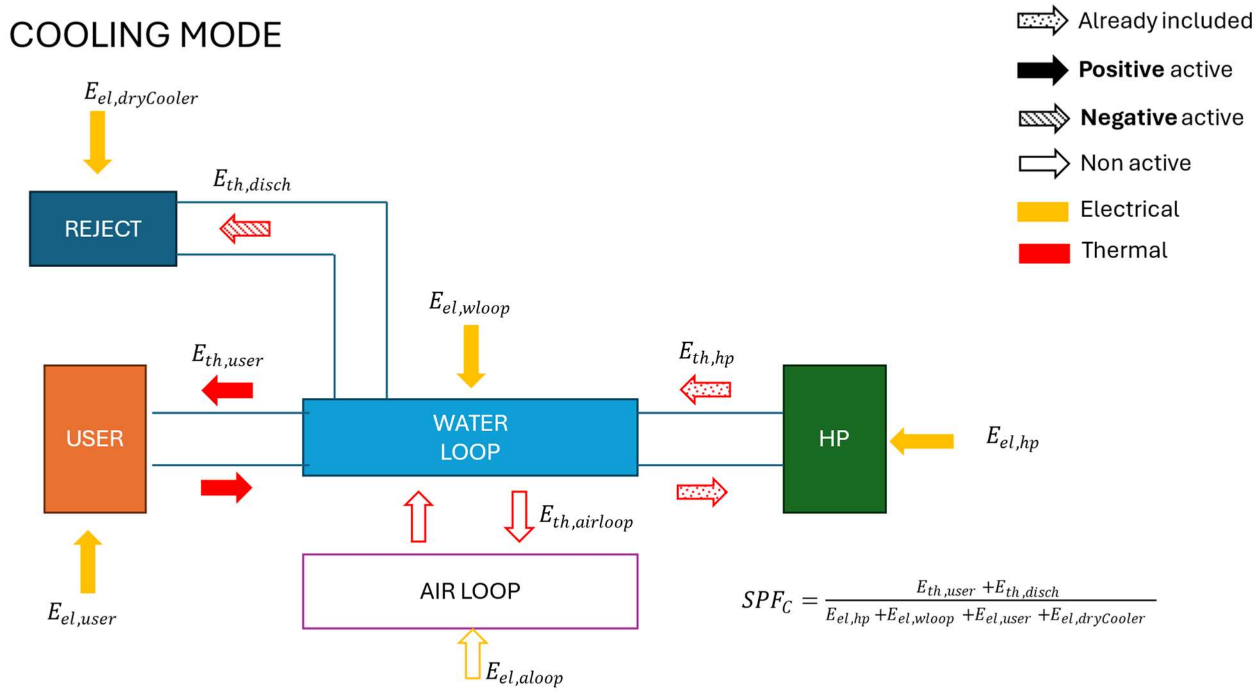

Figure 9. TES device operating in cooling mode

QTI2.2: THERMAL STORAGE CAPACITY	
Description	This indicator quantifies the total amount of thermal energy that can be stored by the TES system in the TCM reactor, representing the system's capacity to retain thermal energy over a specific period.
Units	kWh_t
Equation	$\text{Thermal Storage Capacity} = \mathit{Storage\ Density\ x\ Volume\ of\ Storage}$
Nomenclature	*Storage density:* The amount of energy stored per unit volume of the storage material in kWh/m^3. *Volume of storage:* The total volume for storing thermal energy within the TCM reactor of the TES device in m^3.
How is going to be measured?	*Calculating the product of the measured storage density of the material in the TCM reactor and the total volume for storing thermal energy.*
Phase of the project	Experimental (WP4) and demosite evaluation (WP6)
Evaluation	The 'Thermal Storage Capacity' is a key indicator as it will allow us to evaluate the size or capacity of the TES device. By utilizing the Thermal Storage Capacity, we can standardize subsequent indicators (like production QTI4.1 costs, QTI4.2 maintenance costs, QLI4.3 scalability...), ensuring that our analyses are consistent and meaningful, providing a reliable basis for comparison and assessment of the TES devices. This indicator will be evaluated in deliverables D4.3, D6.1, D6.2 and D6.3.
Limitations and assumptions	The calculation assumes uniform material properties. This measure is considered a gross estimate, accounting for the total potential energy storage without detailing specific losses or efficiency factors during the charge and discharge cycles.

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QTI2.3: EFFICIENCY OF THERMAL STORAGE	
Description	This indicator measures the effectiveness of a system in utilizing stored energy to provide thermal energy to a building, reflecting how efficiently the thermal storage system operates.
Units	Percentage (%)
Equation	$\text{Efficiency (\%)} = \left(\frac{\text{Thermal Energy Provided by thermal storage}}{\text{Energy Stored in thermal storage}} \right) \times 100$
Nomenclature	Thermal Energy Provided by Thermal Storage: The total amount of thermal energy that is delivered to the building from the storage system. Energy Stored in Thermal Storage: The total amount of energy that has been stored within the thermal storage system.
How is going to be measured?	The efficiency will be calculated by comparing the amount of thermal energy provided to the building to the amount of energy that was initially stored in the thermal storage system.
Phase of the project	Experimental (WP4) and demosite evaluation (WP6)
Evaluation	The results will be interpreted to assess the performance of the system, and should be monitored, and later compared with, in demo cases applications. This indicator will be evaluated in deliverables D4.3, D6.1, D6.2 and D6.3.
Limitations and assumptions	Accuracy of instruments must be considered

QTI2.4.1: CHARGING TIME RATE	
Description	This indicator measures the rate at which the thermal storage system is charged with energy, reflecting the efficiency and speed of the charging process.
Units	kWh_t/hour (kilowatt-hours per hour)
Equation	$\text{Charging Time Rate} = \frac{\text{Total Energy Charged}}{\text{Charging Time}}$
Nomenclature	Total Energy Charged: The total amount of energy stored in the thermal storage system during the charging process. Charging Time: The duration of the charging process from start to completion.
How is going to be measured?	The charging time rate will be determined by dividing the total energy charged by the total time taken.
Phase of the project	Experimental (WP4) and demosite evaluation (WP6)
Evaluation	The results will be interpreted to assess the performance of the system during the charge mode, and should be monitored, and later compared with, in demo cases applications. This indicator will be evaluated in deliverables D4.3, D6.1, D6.2 and D6.3.
Limitations and assumptions	Accuracy of instruments must be considered. The calculation presumes uniform energy input throughout the charging duration. It is assumed that the charging process is uninterrupted during the charging time.

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QTI2.4.2: DISCHARGING TIME RATE	
Description	This indicator quantifies the rate at which the thermal storage system releases the stored energy, indicating the efficiency and speed of the discharging process.
Units	kWh_t/hour (kilowatt-hours per hour)
Equation	$$\text{Discharging Rate} = \frac{\text{Total Energy Discharged}}{\text{Discharging Time}}$$
Nomenclature	Total Energy Discharged: The total amount of energy released from the thermal storage system during the discharging process. Discharging Time: The duration of the discharging process from start to completion.
How is going to be measured?	The discharging time rate will be determined by dividing the total energy discharged by the total time taken.
Phase of the project	Experimental (WP4) and demosite evaluation (WP6)
Evaluation	The results will be interpreted to assess the performance of the system during the discharge mode, and should be monitored, and later compared with, in demo cases applications. This indicator will be evaluated in deliverables D4.3, D6.1, D6.2 and D6.3.
Limitations and assumptions	Accuracy of instruments must be considered. The calculation presumes uniform energy output throughout the discharging duration. It is assumed that the discharging process is uninterrupted during the discharging time.

5.1.3 Social & Environmental indicators

Social and environmental indicators are critical in determining the impact and sustainability of this system on society and the environment. The indicators included in this category are:

QTI3.1: CO_2 EMISSIONS REDUCTION	
Description	It measures the reduction of equivalent CO_2 emissions in the grid due to the activation of a flexibility action compared to the initial emissions related to the generation mix
Units	no units
Equation	$$EI = \frac{\sum_{h=1}^{24}(Ec_h \cdot f_h^{CO_2}) - \sum_{h'=1}^{h'+d}(Ec_h \cdot f_h^{CO_2}) + \sum_{h''=1}^{h''+t_{rec}}(Ec_h \cdot f_h^{CO_2})}{\sum_{h=1}^{24}(Ec_h \cdot f_h^{CO_2})}$$
Nomenclature	Ec_h is the energy consumption for each hour during the evaluated day f_h^{CO2} is the mean emissions factor for the generation mix during the hour h h' is the hour where the flexibility action starts d is the duration of the flexibility action h'' is the hour where the recovery period starts. The recovery period is the time during which the consumer retakes the consumption reduced during the flexibility action. It may be split into different parts t_{rec} is the duration of the recovery period
How is going to be measured?	Emission factors are usually published by the TSO (in Spain, they are available at the web www.esios.ree.es). The distribution company will provide initial consumptions. The model of the grid developed in task 2.3 will provide consumptions during the flexibility action and recovery periods.

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Phase of the project	T2.4 - Simulation (electric grid)
Evaluation	This indicator will be evaluated in Deliverable D2.4 of the project, measuring the percentage in which the net emissions are reduced when compared to the initial value (without the implementation of the flexibility) and it considers the lower energy consumption (and, consequently, lower emissions) during the flexibility action and the consumption increment during the recovery period. Possible values for this factor are: EI>1: The impact is positive (there is a net reduction of emissions). The larger is EI, the higher is the positive impact to the grid. EI=1: There is no impact. It does not mean that the energy reduction is zero or that flexibility is zero, but the emissions reduced during the flexibility action are compensated by the increment of emissions during the recovery period. EI<1: The impact is negative (there is an increment of emissions)

QTI3.2: LIFE CYCLE ANALYSIS (LCA)	
Description	This indicator measures the potential environmental impacts reduction thanks to ECHO TES system implementation.
Units	Global warming potential (GWP), the use of primary energy resources (both renewable and non-renewable) and ozone layer depletion potential (ODP) among others
How is going to be measured?	Standardised Life Cycle Assessment methodology will be applied to analyse the system implemented in the 3 demonstration facilities.
Phase of the project	Demosite evaluation (WP6)
Evaluation	The environmental characterization of TES device systems will be comprehensively determined, underscoring the potential environmental advantages by contrasting with a scenario devoid of the ECHO TES implementation. This indicator will be evaluated in deliverable D7.1.

5.1.4 Market & Regulation indicators

The indicators of this section provide valuable insights into the economic viability, scalability and adherence to regulatory standards of the ECHO TES solution. The market and regulation indicators proposed are:

QTI4.1: COST - LIFE CYCLE COST ANALYSIS (LCCA)	
Description	This indicator aims to analyse the costs of ECHO TES implementation.
Units	€/kWh storage capacity
Equation	$\text{Cost} = \frac{\text{Total Cost of TES System}}{\text{Energy Storage Capacity}}$
How is going to be measured?	The analysis will consider the costs of the TES system manufacturing, installation and operation according to market prices of the specific locations of the demonstration facilities
Phase of the project	Demosite evaluation (WP6)
Evaluation	The cost indicator will provide insights into the economic viability, aiding in financial decision-making. This indicator will be evaluated in deliverable D7.1.

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Limitations and assumptions (if needed)	It is important to note that the costs associated with a prototype may differ significantly from those incurred during mass production, as economies of scale and optimized manufacturing processes can reduce costs in serial production.

QTI4.2: MAINTENANCE COST	
Description	This indicator assesses the maintenance demands of the TES system.
Units	€/ year / kWh storage capacity
Equation	The maintenance cost will be calculated annually and presented in €/year per kWh storage capacity.
How is going to be measured?	The cost associated with maintaining the TES system over a one-year period
Phase of the project	Demosite evaluation (WP6)
Evaluation	This indicator will help evaluate the maintenance efficiency, influencing the overall operational cost and reliability of the TES system. This indicator will be attempted to estimate during the evaluation of the demosites (deliverables D6.1, D6.2 and D6.3).
Limitations and assumptions (if needed)	It is assumed that the maintenance activities are consistent each year and that the costs calculated reflect the actual expenses incurred.

5.2 Qualitative Indicators

5.2.1 Electricity grid indicators

The electricity grid indicators category plays a significant role in evaluating and enhancing the effectiveness of energy systems. The identified indicator within this category is:

QLI1.1: GRID ELECTRICTY MIX	
Description	This indicator assesses the composition of energy sources used to generate electricity within a specific location, including the proportion of renewable energy sources. The electrical mix may vary in the time of day that electricity is consumed.
Units	Dimensionless (scale from 0 to 10)
Equation	The electrical mix is quantified on a scale from 0 to 10, where 0 represents no use of renewable sources and 10 indicates exclusive use ofrenewable sources.
How is going to be measured?	The electrical mix will be determined based on the proportion of various energy sources used in each demosite location, with a specific focus on the share of renewable energy within the total mix.
Phase of the project	Demosite evaluation (WP6)
Evaluation	This indicator will be analysed to gauge the sustainability potential of the electricity grid, which could be leveraged by the TES device. This indicator will be evaluated in deliverables D6.1, D6.2 and D6.3.
Limitations and assumptions (if needed)	The calculation assumes that accurate data on the proportion of different energy sources used in electricity generation is available and reliable.

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5.2.2 Energy indicators

The qualitative indicator considered for this category is:

QLI2.1: INTEGRATION WITH ENERGY MANAGEMENT SYSTEMS (ECHOTSS)	
Description	This indicator evaluates the extent of successful integration between the ECHOTSS systems and the energy management systems (EMS). It focuses on the TES device's ability to collaborate effectively with EMS to optimize energy usage, support grid stability, and respond to market demands.
Units	Dimensionless (scale from 0 to 10)
Equation	The integration with energy management systems result is a dimensionless number from 1 to 10.
How is going to be measured?	The integration level will be assessed based on the system's responsiveness to market price signals, its contribution to energy efficiency, and its support for renewable energy integration within the electric market.
Phase of the project	Demosite evaluation (WP6)
Evaluation	A higher score indicates a more effective and seamless integration of the TES device with the EMS in the electric market. This indicator will be evaluated in deliverables D6.1, D6.2 and D6.3.
Limitations and assumptions (if needed)	The scoring is based on predefined parameters that may need periodic review during the demosite evaluation.

5.2.3 Social & Environmental indicators

The aim of the qualitative indicator in this category is to measure the system influence and long-term sustainability within society and the ecosystem. The indicator that has been considered is:

QLI3.1: COMMUNITY ACCEPTANCE LEVEL FOR TES DEVICES	
Description	This metric evaluates the level of community acceptance for TES devices, assessing public perception, understanding, and support. It considers the devices' impact on energy efficiency, environmental sustainability, and their integration into local communities.
Units	Categorized levels - High, Medium, Low
Equation	Community acceptance is gauged through public surveys and community feedback, which assess awareness of TES benefits, perceived environmental impacts, and the integration of TES devices into local energy systems.
How is going to be measured?	The level of community acceptance will be determined through surveys and feedback workshops designed to capture public opinion regarding TES devices.
Phase of the project	Demosite evaluation (WP6)
Evaluation	High Acceptance: Indicates strong community support and a comprehensive understanding of TES devices' value. Medium Acceptance: Indicates moderate support and understanding, with some reservations or lack of information. Low Acceptance: Indicates minimal support and understanding, possibly due to misconceptions or lack of awareness. This indicator will be evaluated in deliverable D8.4

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Limitations and assumptions (if needed)	Interpretations of acceptance levels are based on the assumption that the community is adequately informed and that the feedback collected is an accurate reflection of public opinion

5.2.4 Market & Regulation indicators

As mentioned before, the indicators of this section provide valuable insights into the economic viability, scalability and adherence to regulatory standards of the ECHO TES solution. The indicators that have been considered are:

QLI4.1: LEGISLATIVE PENETRABILITY FOR TES TECHNOLOGY	
Description	This indicator evaluates the regulatory environment influencing the demand flexibility market, especially regarding norms and regulations related to TES devices. It assesses how current regulations are clear, supportive, and adaptable in fostering demand flexibility and the integration of TES technologies.
Units	Categorized levels - Supportive, Neutral, Restrictive
Equation	The assessment is conducted through a thorough SWOT analysis of the existing regulatory landscape (Task 2.1) for the countries of participating partners, examining how regulations impact the use and integration of TES devices in demand flexibility markets.
How is going to be measured?	The categorization into Supportive, Neutral, or Restrictive will be based on an analysis of factors such as regulatory incentives for TES integration, market entry barriers for new technologies, and legal frameworks that enable or restrict demand flexibility.
Phase of the project	Simulation T2.1
Evaluation	Supportive (High): Indicates a regulatory framework that actively encourages and promotes the adoption and integration of TES devices, facilitating market entry and operation. Neutral (Medium): Indicates a regulatory framework that neither significantly impedes nor actively promotes the use of TES devices in demand flexibility. Restrictive (Low): Indicates a regulatory environment that poses significant barriers to the integration of TES devices in demand flexibility markets, potentially through stringent regulations or lack of supportive legal frameworks. This indicator will be evaluated in deliverables D2.1
Limitations and assumptions (if needed)	The assessment assumes comprehensive access to current regulations and an accurate interpretation of their implications for TES and demand flexibility. The analysis is contingent on the prevailing regulatory landscape at the time of assessment, acknowledging that regulations can evolve.

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QLI4.2: RELIABILITY	
Description	This indicator assesses the TES system's reliability, durability, and safety, emphasizing the system's design to minimize risks of accidents or damage to property and individuals. It evaluates how consistently the TES system performs as expected under various conditions while adhering to relevant safety standards.
Units	Categorized levels - High, Moderate, Low
Equation	Reliability is assessed based on the system's adherence to establish safety standards, its performance consistency across different operating conditions, and its track record in incidents.
How is going to be measured?	The level of reliability and safety will be determined through evaluations of the system's performance stability during the demosite evaluation.
Phase of the project	Demosite evaluation (WP6)
Evaluation	High Reliability: Indicates that the TES device consistently performs as expected across a range of conditions and complies with all relevant safety standards, showing minimal risk of accidents or damage. Moderate Reliability: Suggests that the TES system generally performs reliably and is mostly compliant with safety standards, but there may be some areas for improvement. Low Reliability: Points to potential reliability issues or safety concerns, indicating that the system does not consistently meet expected performance levels or safety standards. This indicator will be evaluated in deliverables D6.1, D6.2 and D6.3.
Limitations and assumptions (if needed)	The assessment is subject to the time constraints associated with each demo site's evaluation period, which may not fully capture long-term reliability.

QLI4.3: SCALABILITY	
Description	This indicator evaluates the TES system's scalability, which refers to its ability to be expanded or reduced in size to accommodate different energy demands without compromising its functionality.
Units	Categorized levels - High Scalability, Moderate Scalability, Low Scalability
Equation	Scalability is assessed based on the system's adaptability to changes in size or capacity, considering factors such as ease of modification, associated costs, and impact on performance.
How is going to be measured?	Scalability will be evaluated through analysis of design flexibility of the different demosite facility.
Phase of the project	Experimental (WP4-WP6)
Evaluation	High Scalability: Indicates that the TES system can be efficiently scaled to different sizes or capacities while maintaining functionality and cost-effectiveness. Moderate Scalability: Suggests that the TES system has some degree of scalability, but there may be limitations or increased costs associated with significant size adjustments. Low Scalability: Implies that the TES system has limited scalability, with substantial challenges or costs involved in modifying its size or capacity.

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	This indicator will be thoroughly evaluated during WP4 and WP6.
Limitations and assumptions (if needed)	It is assumed that the assessment of scalability cannot consider the broader system context, including integration with existing infrastructure and energy markets.

Finally, as a summary, Table 1 is presented, which consolidates all the developed indicators. This table specifies the typology of each indicator, distinguishing between quantitative and qualitative, indicates in which phase of the project each one is evaluated, and identifies the deliverable in which the results of such evaluation are compiled. This table serves as a quick reference tool to understand the scope and methodology of the indicators' evaluation throughout the project.

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Table 1. Summary of the T2.2 indicators

			Type of indicator		Phase of the project			Evaluated							
			Quantitative	Qualitative	Simulation	Experimental	Demosite	D2.1	D2.4	D4.3	D6.1	D6.2	D6.3	D7.1	D8.4
ELECTRICITY GRID INDICATORS	QTI1.1	**Global Energy Efficiency**	●				●				●	●	●		
	QTI1.2	**Market Flexibility**	●		●				●						
	QTI1.3	**Peak Saving Potential**	●		●				●						
	QTI1.4	**Renewable Energy from Grid**													
	QLI1.1	**Grid Electricity Mix**		●			●				●	●	●		
ENERGY INDICATORS	QTI2.1.1	**SPF (recharge)**	●			●	●			●	●	●	●		
	QTI2.1.2	**SPF (discharge)**	●			●	●			●	●	●	●		
	QTI2.1.3	**SPF (cooling)**	●			●	●			●	●	●	●		
	QTI2.2	**Thermal Storage Capacity**	●			●	●			●	●	●	●		
	QTI2.3	**Efficiency of Thermal Storage**	●			●	●			●	●	●	●		
	QTI2.4.1	**Charging time rate**	●			●	●			●	●	●	●		
	QTI2.4.2	**Discharging time rate**	●			●	●			●	●	●	●		
	QLI2.1	**Integration with ECHOTSS**		●			●				●	●	●		
SOCIAL INDICATORS	QTI3.1	**CO_2 Emissions Reduction**	●		●				●						
	QTI3.2	**Life Cycle Analysis**	●				●							●	
	QLI3.1	**Community Acceptance**		●			●								●
MARKET INDICATORS	QTI4.1	**Life Cycle Cost Analysis**	●				●							●	
	QTI4.2	**Maintenance Cost**	●				●				●	●	●		
	QLI4.1	**Legislative Penetrability**		●	●			●							
	QLI4.2	**Reliability**		●			●				●	●	●		
	QLI4.3	**Scalability**		●		●	●			●	●	●	●		

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6 Operational parameters

This section delves into the operational parameters of the Thermal Energy Storage (TES) device, a critical component for understanding and evaluating the device's efficiency and functionality. For enhanced clarity, the operational parameters are categorized based on the distinct parts of the TES device. These categories are as follows:

1. **Thermochemical Materials (TCM) Parameters:** This section details the parameters related to the materials used in the TES device that undergo thermochemical transformations, providing insights into their behaviour and performance in energy storage processes.
2. **Phase Change Materials (PCM) Parameters**: It outlines the characteristics of materials that store and release energy through phase transitions and employed in insulation.
3. **Heat Pump Parameters**: This part focuses on the operational metrics of the heat pump within the TES system.
4. **TCMs Reactor Parameters:** It presents the specific parameters that define the performance of the reactor where the thermochemical processes occur.
5. **Heat Exchanger Parameters:** This section covers the parameters that influence the efficiency and effectiveness of heat exchange within the TES device.
6. **ICE Based PCM Materials Parameters:** It elaborates on the parameters of phase change materials based on ice.

It should be noted that, as these tasks are currently in progress, exact values for the operational parameters of the TES device have not been finalized. However, a range of expected values is provided to offer a preliminary understanding of the potential operational scope and limitations of the TES device.

6.1.1 Thermochemical Materials (TCM) parameters

TCMs, such as salt hydrates (Salt·xH_2O), absorb heat from low-temperature sources during charging, breaking molecular bonds and storing thermal energy as chemical potential. During discharging, they release heat when salt recombines with water molecules. However, pure salt hydrates have poor heat and mass transfer properties, causing clumping and expansion in the Thermochemical Energy Storage (TCES) system, reducing efficiency. One solution is to combine salt hydrates with porous materials, enhancing heat and mass transfer, preventing clumping and expansion, and improving efficiency and stability. However, the energy storage density of TCM composite materials synthesized through the conventional single impregnation method is relatively low. Alternatively, four different approaches were proposed, namely multi-step impregnation, vacuum impregnation, high-pressure impregnation, and high-temperature high-concentration impregnation. Samples were prepared using the conventional single impregnation methods (VCM-s) and the abovementioned four different methods. Based on the material characterization results, the sample synthesized via vacuum impregnation (VCM-vac) were exhibited in *Table 2*. The structural parameters were determined using mercury porosimetry, revealing that VCM-vac has smaller pore volume and bulk density compared to VCM-s. Based on this information, it can be inferred that VCM-vac has a higher $CaCl_2$ content. This was confirmed by $CaCl_2$ content testing using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), which showed that VCM-s and VCM-vac contain 51% and 72% $CaCl_2$, respectively. The vacuum impregnation technique not only increased the $CaCl_2$ content in the composites by 21% but also nearly doubled the volumetric energy storage density of the composites (2.05 GJ/m^3). During 20 cycles testing, both VCM-s and VCM-vac exhibited relatively stable performance. The energy consumption during the synthesis process of VCM-vac was slightly higher than that of VCM-s due to the additional vacuum step, but the difference was not significant compared to other VCMs.

In summary, vacuum impregnation is a promising alternative synthesis method for the preparation of thermochemical composite materials.

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Table 2. Structure and performance parameters of VCM-s and VCM-vac

Parameters	Expected range
Porosity (%)	45 – 75
Particle bulk density (g/cm^3)	0.4 – 0.8
$CaCl_2$ content (%)	45 – 83
VESD based on particle (GJ/m^3)	0.8 – 2.1
Water uptake decreases after 20 cycles (%)	10 – 15
Weight after 20 cycles (%)	90 – 95
Energy consumption of fabrication (kWh/kgsalt)	3 – 30

6.1.2 Phase Change Materials (PCM) parameters [1]

The PCM is an important part of the TES system since serves as an energy buffer and storage to produce the water vapour at the appropriate partial pressure that is needed for the thermochemical transformations into the TCM reactor, as well as for insulation.

Thermal energy transfer occurs when PCM is melted from solid to liquid or solidified from liquid to solid. During the PCM phase transition, thermal energy is stored or recovered. The phase transition of PCM occurs at almost constant temperature and the choice of this element is based on the thermophysical, chemical, kinetic and economic properties.

Most PCMs can be classified into 3 categories (organic, inorganic and eutectic) based on composition. Figure 10 shows the PCM types depending on melting temperature and enthalpy.

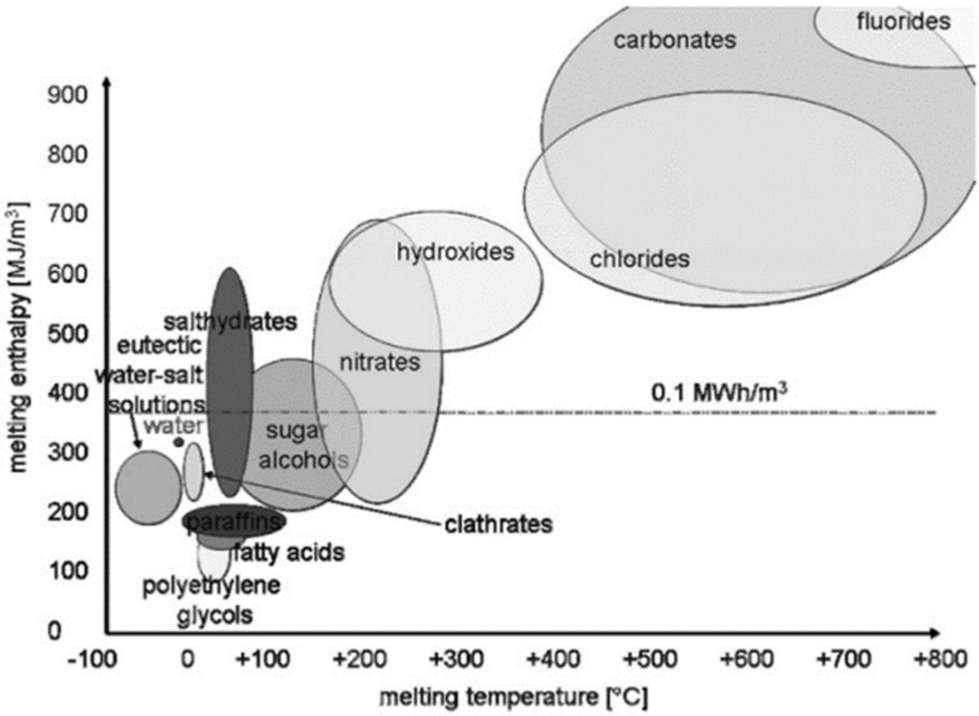

Figure 10. PCM types depending on melting temperature and enthalpy

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Focusing on the energy buffer and storage to produce the water vapour application, considering the temperature range for this specific application (27-35°C), the chemical stability, the volumetric heat capacity and above all the availability on the market of products that can be used for the project, organic PCMs based on paraffins and inorganic ones, as salt hydrates, are the most attractive.

Paraffins are considered as widely available, economical and non-corrosive products. Furthermore, from a chemical point of view, they are inert and stable, and their volume does not significantly change with the phase changes. The main disadvantages are flammability, low density and low thermal conductivity.

Table 3 reports the properties of A32 PCM that will be considered as possible solution.

Table 3. Properties of A32 PCM, as declared by PCM PRODUCTS

A32 PCM	Phase change T (°C)	Density (kg/m³)	Latent Heat Capacity (kJ/kg)	Volumetric Heat Capacity (MJ/m³)	Specific Heat Capacity (kJ/kgK)	Thermal Conductivity (W/mK)	Maximum Operating Temperature (°C)
	32	845	120	101	2.2	0.121	200

In order to evaluate the PCM properties, including stability, Differential Scanning Calorimetry (DSC) experiments have been performed. The experiments consist of 20 melting/crystallization cycles by temperature scans at 2°C/min around the transition temperatures with the aim of also evaluating the thermal storage capacities and their modifications with cycles (see *Table 4*).

Table 4. Properties of A32 PCM measured by DSC

A32 PCM	
Grav. Latent Heat (2 K min^{-1})	165 kJ/kg
Vol. Latent Heat (2 K min^{-1})	139 MJ m^{-3}
Subcooling (peak to peak)	2°C
Cyclability	Very good

Regarding the inorganic PCMs, they have a higher latent heat per volume due to their higher density, and lower cost, and most of them are not flammable. On the other side, they suffer from subcooling and lower stability with cycles.

Therefore, salt hydrates have a thermal conductivity and volumetric latent heat capacity higher than that of organic PCMs. However, in most, but not all cases, salt hydrates are chemically very stable and potentially corrosive.

Among the salt hydrates available on the market, the S32, S32A and S32B have been tested for this application (*Table 5*).

Table 5. Properties of S32 PCM, as declared by PCM PRODUCTS

S32 PCM	Phase change T (°C)	Density (kg/m³)	Latent Heat Capacity (kJ/kg)	Volumetric Heat Capacity (MJ/m³)	Specific Heat Capacity (kJ/kgK)	Thermal Conductivity (W/mK)	Maximum Operating Temperature (°C)
	32	1460	220	321	1.9	0.51	60

To evaluate the PCM properties, further Differential Scanning Calorimetry (DSC) experiments have been performed (*Table 6*).

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Table 6. Properties of S32 PCM measured by DSC

S32 PCM	
Avg. Grav. Latent Heat (2 K min^{-1})	134 kJ/kg
Avg. Vol. Latent Heat (2 K min^{-1})	196 MJ m^{-3}
Grav. Latent Heat (0.3 K min^{-1})	204 J g^{-1}
Vol. Latent Heat (0.3 K min^{-1})	298 MJ m^{-3}
Subcooling (peak to peak)	10°C
Cyclability	Moderate

To sum up, the expected values for the organic PCM (A32), hydrated salt (S32) and ice eutectic (E0) are described in *Table 6*.

Table 7. Expected values for the PCMs A32, S32 and E0

PCM	Phase change T (°C)	Density (kg/m³)	Latent Heat Capacity (kJ/kg)	Volumetric Heat Capacity (MJ/m³)	Specific Heat Capacity (kJ/kgK)	Thermal Conductivity (W/mK)	Maximum Operating Temperature (°C)
A32	32	790	160	126	2.22	0.21	200
S32	32	1460	150	219	1.9	0.51	60
E0	0	1000	335	335	4.19	0.58	100

According to the previous values, it is possible to obtain ranges of the parameters for the studied demosites.

Table 8. Range for the PCMs A32, S32 and E0 parameters

Phase change T (°C)	Density (kg/m³)	Latent Heat Capacity (kJ/kg)	Volumetric Heat Capacity (MJ/m³)	Specific Heat Capacity (kJ/kgK)	Thermal Conductivity (W/mK)	Maximum Operating Temperature (°C)
0 – 32	790 – 1460	150 – 335	126 – 335	1.9 – 4.19	0.21 – 0.58	60 – 200

Moreover, as refer the insulations for the TCMs reactor and the cold accumulator, based on the required insulation properties, the selected organic PCM was ethyl palmite. It has melting onset and peak points at 21°C and 23°C, whereas the melting enthalpy is equal to 182 kJ/kg. Its DSC thermogram is given in *Figure 11*. However, other analyses are ongoing on butyl stereate, for its properties similar to ethyl palmite, but higher facility in gathering raw materials from the market.

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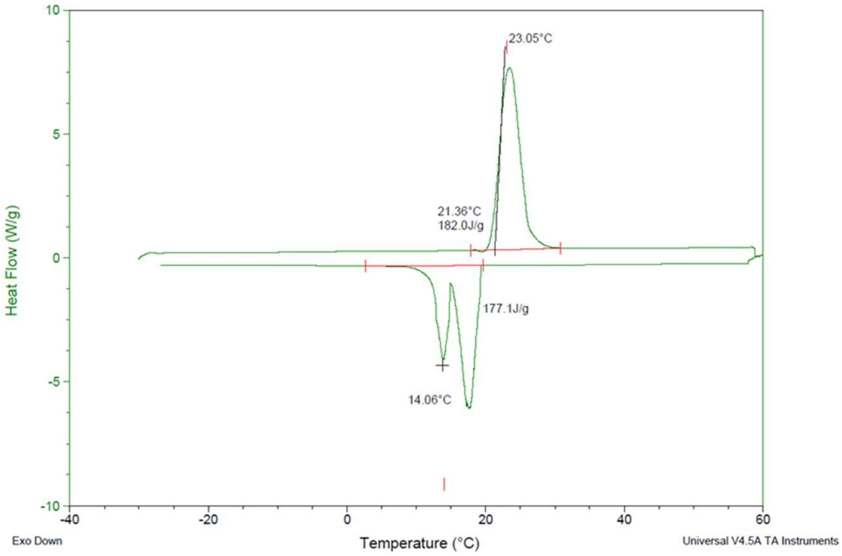

Figure 11. DSC thermogram of ethyl palmitate

Rigid polyurethane (PU) foams perform well in most areas of low-temperature insulations. Compared with other insulating materials, PU rigid foam is highly competitive. There are several advantages: lowest thermal conductivity, high mechanical and chemical properties at both high and low temperatures and the ability to form sandwich structures with various facer materials. Products in density ranging from approximately 30 to 200 kg m^{-3} withstand temperatures down to -196°C. Typical applications are: refrigerated vehicles, road and rail tankers, vessels for refrigerated cargo, pipelines, liquid gas tanks for liquified petroleum gas (LPG) and liquified natural gas (LNG) and cryogenic wind tunnels. However, it is possible to enhance their heat absorption capacity with incorporation of PCMs. In general, PU-PCM composites have larger heat absorption capacity in terms of specific and latent heat.

The main polyurethane (PU) rigid foam formulation has been developed and raw materials have been supplied by Ideakim Global for synthesis. The virgin foam formulation and its determined properties are given in Table 9.

Table 9. Virgin PU rigid foam formulation and its determined properties

Raw Material	Parts
NJ-8238	50.9
IDEAPOL 400-3	20
DMCHA	0.3
POLYCAT 41	0.3
IDEASIL 350	2
TCPP	19
WATER	1.9
CYCLOPENTANE	5.6
PMDI	130
Properties	**Value**
T_{iso} (°C)[1]	22
T_{pol} (°C)[1]	22

[1] T_{iso} is the Temperature of isocynate part, T_{pol} the Temperature of Polyol part.

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Cream time (s)	44
Gel time (s)	215
Tack-free time (s)	385

The PU-PCM composites produced in lab-scale contain 5, 10 and 15 wt. % PCM in PU foam and they are seen in the photos given in Figure 12. For 15 wt. % PCM content, composite sample containing twice of the original foaming agent (cyclopentane) has also been studied to observe the effect of the modification. The thermal conductivity of the foams in Figure 12 are in the range of 0.028 - 0.040 W/m.K at room temperature.

Figure 12. PU-PCM composites containing different amounts of PCM

6.1.3 Heat Pump Parameters

A heat pump is a crucial component of a TES system, owing to its ability to generate thermal energy, which is necessary for charging and discharging thermal energy storage systems.

It is worth noting that the refrigerant R515B will be used, and the configuration will be a glycolate-water (evaporator) - water heat pump system. Also, COP will be calculated considering the sum of evaporator capacity (temperatures and mass flow rate of glycolate water) and the compressor power input. This value will be compared with the thermal balance and validated with the pressure of evaporator and condensation and polynomials of compressor's manufacturer.

Two independent measurements will provide us a good precision and in case of different results in steady state regime, it can be assumed that there is a data acquisition problem.
The working expected range of the main parameters are defined in the following table (see *Table 10*).

Table 10. Expected values for the heat pump

Parameter	Range
Condensing Power (kW)	7 – 8
Evaporating Power (kW)	3.8 – 4.0
Electrical power absorbed by the compressor (kW)	3.3 – 4.0
Frecuency of the compressor (Hz)	46 – 60
Evaporative temperature range (°C)	0 – 3.5
Condensing temperature range (°C)	83 – 86

The values showed in *Table 10* are valid under these conditions:

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- The absolute humidity at the inlet of the TCM is 6.5 g/kg
- The temperature at the inlet of the TCM is 80 °C
- The extraction of vapour is 3 g/kg per kg/s of air

6.1.4 TCMs Reactor Parameters

Table 11 The thermochemical reactor is a key component of the storage system. Based on experimental and simulation data, the parameter range for the full-size TCM reactor is determined as shown in Table 11. To meet the output power requirement of 3kW, a total of 150-250 kg of TCM is required, along with 10-20 m^2 of frontal area. A of 0.02-0.04 m/s (690-1366 m^3/h) passes through the TCM reaction bed.

Table 11. Parameters of TCM reactor

Parameter	Expected range
TCM mass	150-250 kg
TCM density in reaction bed	200 – 400 kg/m^3
TCM Porosity in reaction bed	65 – 85 %
$CaCl_2$ content	45 – 85 %
Volumetric energy storage density	150 – 210 kWh/m^3
Frontal Area	10 – 20 m^2
Average power	> 20 – 25 W/kg
Air flow rate	680-1400 m^3/h

6.1.5 Heat Exchanger Parameters

With the aim of fulfilling the project's needs, Microchannel Heat Exchangers (MCHEs) are specifically designed and manufactured to cover a wide range of operating conditions. However, their utilization in TCMs reactors, as well as in the heat pumps or in any other heat transfer device, has to consider some working pressure and temperature limitations.

In general, the design parameters mainly depend on the used working fluids. In the frame of this project, the MCHE will be used with regular water or, potentially, with water/glycol mixtures. This follows that the actual working conditions must respect the operating limits as defined in *Table 12*:

Table 12. MCHEs design parameters with working range

Parameters	Working range
Design pressure	1 – 4.5 MPa
Burst pressure	3 – 13.5 MPa
External side temperatures	-40°C to 70°C
Internal side temperatures	-40°C to 121°C

Both the fins and tube are produced with 3103 LLA (Long Life Alloy). This material presents quite good resistance when used in medium corrosive environments (*ISO 9223:2012*). However, when an aluminum heat exchanger is used in water systems, there is a significant risk of leakages due to galvanic, impact or cavitation corrosion. Some of the parameters have been analyzed that might impact on the aluminum corrosion:

1. ***Working pressure and temperatures*** *(refers to Table 12)*
2. ***Working Fluid:*** Factors, such as pH values, deterioration of passivated layer due to solid particles and utilization of specific corrosion inhibitors, have a significant impact on corrosion. While selecting the working fluids, Sanhua suggests meeting the following requirements:

a. The refrigerating liquid shall be a mixture of water, ethylene glycol, and corrosion inhibitors. The utilization of deionized water as per ASTM1193 (Types Ⅰ-Ⅳ) is highly recommended.
b. The fluid pH must fall in a range between 7 and 8.2.
c. Corrosion inhibitors are recommended as follows:
    i. Organic acids (carboxylate).
    ii. Mixture of organic acids and phosphates.
    iii. Mixture of low silicates fluids with organic acids.
    iv. Long-acting inhibitor used by North American, European and Asian automotive manufacturers.
    v. Other inhibitor systems, such as nitrate-aluminum pitting, anti-foaming agents (ASTM D1881), Anti-cavitation agent (ASTM D2809), bitter agent, etc. Etc.

In addition to that, it is recommended that the concentration of the mixture (glycol + inhibitor) in water should stay between 25- 60% (volume). In the market there are different commercial brands of this blend (glycol + inhibitor) ready to use for which you should also refer to their working guidelines.

3. *The fluid Velocity*: In general, the higher the flow rate, the stronger the shear and the impact effect on the metal surface is. The material suffers corrosion or heavy erosion phenomena especially when solid particles begin to appear in the fluid. The maximum allowable velocity is 1.4m/s.

4. *Material of the system parts*: The use of brass and copper in other water system components should be avoided. In the case this condition cannot be fully respected, the utilization of other metals should be minimized. If copper/brass components are used, the distance from MCHE should be at least *5mm (about 0.2 in)*. Non-metallic parts should be compatible with the working fluids avoiding any chemical reaction risk within the operating pressure and temperature limits as defined in *Table 12*.

6.1.6 ICE based PCM Materials Parameters [2]

Inorganic materials cover a wide temperature range. Compared to organic materials, inorganic materials usually have similar melting enthalpies per mass, but higher ones per volume due to their high density. Their main disadvantage is material compatibility with metals, since severe corrosion can be developed in some PCM-metal combinations.

Eutectic mixtures are mixtures of two or more constituents, which solidify simultaneously out of the liquid at a minimum freezing point, also called eutectic point. Therefore, eutectic compositions do not show phase separation. Eutectic water-salt solutions have melting temperatures below 0 °C, because the addition of the salt reduces the melting temperature, and usually good storage density. Water-salt solutions consist of two components, water and salt, which means phase separation could be a problem. To prevent phase separation, and to achieve a good cycling stability, eutectic compositions are used. Eutectic compositions are mixtures of two or more constituents, which solidify simultaneously out of the liquid at a minimum freezing point. Therefore, none of the phases can sink down due to a different density. Further on, eutectic compositions show a melting temperature and good storage density. The thermal conductivity of eutectic water-salt solutions is similar to that of water, and they can sub-cool like water. Examples of eutectic water-salt solutions are given in *Table 13*.

Water-salt solutions are chemically very stable, but can cause corrosion to other materials like metals. Compared to water, the addition of a salt usually makes the problem worse. Most of the salt solutions are rather safe, but should not leak in larger amounts. They are usually cheap, often less than 1 €/kg, and therefore the basis for many commercial PCM used in large-scale applications.

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Table 13. Examples of eutectic water-salt solutions

Eutectic Composition	Melting Temperature (°C)	Melting Enthalpy (kJ/kg)
$Al(NO_3)_3$ (30.5 wt.%) + H_2O	-30.6	131
NaCl (22.4 wt.%) + H_2O	-21.2	222
KCl (19.5 wt.%) + H_2O	-10.7	283
H_2O	0	333

With the aim of fulfilling the project goals, two inorganic salts have been chosen to determine their eutectic points. Thus, $MgSO_4.7H_2O$ and Na_2CO_3 are promising candidates for further eutectic point studies, especially the second one considering a higher melting point (around -3°C). $TİO_2$ is used as crystallization agent to suppress possible subcooling effect during freezing. The main goal is a eutectic mixture with known composition, which melts as a single material around –3 °C with high latent heat of fusion. These eutectics will be used in macro-encapsulated forms to provide a protective boundary and a controllable volume to prevent any adverse effect from surrounding and leakage.

7 Case Studies and Demonstration

Three real demonstration installations will be developed by adapting the system to the existing heating/cooling devices in the demo cases. The obtained information will be used to monitor and evaluate the performance, adaptability, functionality, flexibility and reliability of the TES solution under different conditions and the results will be used to evaluate the improvement brought by the ECHO TES device and a series of protocols for installation and use will be developed.

7.1 Research Area of CNR in Padova, Italy (demonstration site nº 1):

The complete ECHO TES solution (TCMs reactor, PCM accumulator and ice storage) will be tested in a building located inside the Research Area of CNR in Padova, Italy. The building was built in 1993 as a single-story office building with a structure made of prefabricated polyurethane walls, with an area higher than 70m^2 and an orientation close to North-South (*Figure*).

Figure 21. Demonstration site No 1 in Padova, Italy

The air conditioning system is currently made by a couple of geothermal heat pumps, which operate alternatively. Each heat pump is equipped with a 200-l tank devoted to the Domestic Hot Water. Moreover,

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they provide hot and cold water to a 180-l thermal storage tank that serves the heating&cooling system of the building (fan coil units).

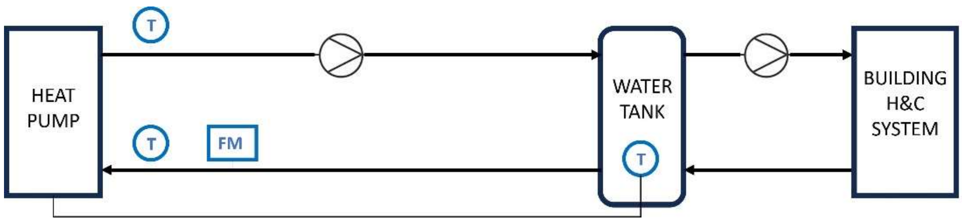

Figure 13. Scheme of the current layout of the heating&cooling system of the CNR pilot site

The hydraulic layout of the CNR pilot (*Figure 13*) will be refurbished in such a way to operate with the newly installed TES system. The final configuration of the TES systems as well as of the hydraulic layout are still being discussed; however, a scheme of the possible new configuration, shown in *Figure 14* was proposed at last M12 General Assembly in Nottingham.

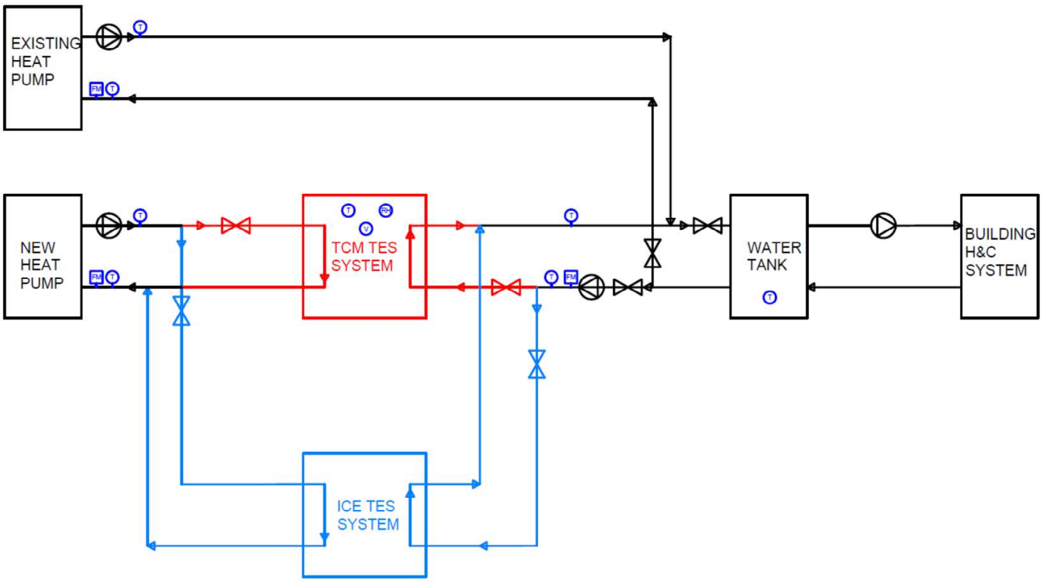

Figure 14. Scheme of the potential layout of the new heating& cooling system with the TES systems

7.1.1 Thermal load assessment

Energy simulations were carried out via Trnsys software to assess the energy demand of the building. In *Table 14* the heating and cooling energy demand of the building is shown on a monthly basis: the negative values in summer mean that the thermal energy is extracted from the building by the HVAC system. The overall energy demand of the building is equal to 10273 kWh in winter and 170 kWh in summer.

The heating demand of the building is two orders of magnitude higher than the cooling one. This is basically due to the presence of some tall trees that shadow the building in the summer mornings, reducing the cooling demand of the building. Furthermore, the walls have a very low heat capacity and a quite low thermal transmittance. The energy simulations highlighted that the building was even cooled during the night, since the external temperature is lower than the internal one, resulting in a reduction of the cooling demand of

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the building. Finally, no internal loads (neither people nor appliances) were taken into account since the building is not usually occupied by CNR personnel.

Additional thermal loads might be artificially added to increase the summer demand of the building in such a way to enhance the analysis of the cooling performance of the systems. Additionally, the set-point temperature of the building could be lowered, taking into account human thermal comfort.

Table 14. Energy demand of the CNR pilot building

Month	Energy demand (kWh)
January	2285
February	1835
March	1451
April	398
May	-1
June	-25
July	-74
August	-64
September	-6
October	561
November	1605
December	2138

7.1.2 Instrumentation and Sensor Deployment

The geothermal system of CNR pilot site is equipped with a large network of sensors aimed at monitoring the most significant parameters, such as temperature, flow rate, electrical energy. The acquisition of such parameters allows to assess the energy performance of the geothermal system. Additional temperature and pressure probes are installed in such a way to evaluate the performance of the refrigerant of the heat pump.

Figure 15 shows a scheme of the monitoring system of the CNR pilot site, whereas Table 15 provides a highlight of the position of the probes.

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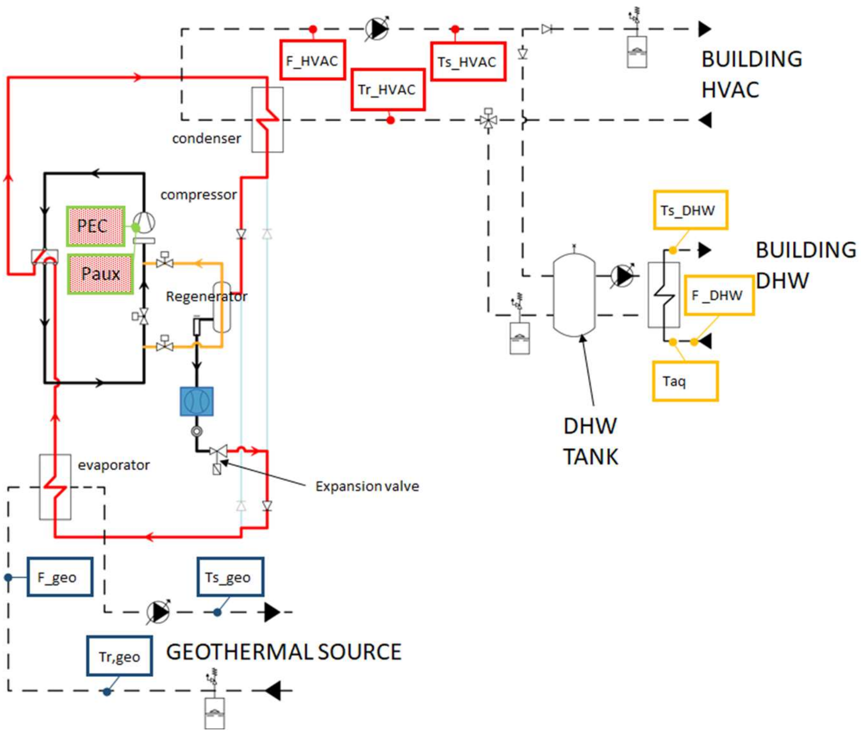

Figure 15. Scheme of the monitoring system of the geothermal system of CNR pilot site

Table 15. Overview of the main probes installed within the geothermal system of CNR pilot site

Code	Parameter	Probe	Measurement
F_HVAC	Flow rate	Electromagnetic flow rate meter	Volumetric flow rate - Building HVAC
Ts_HVAC	Water temperature	RTD sensor	Supply temperature – Building HVAC
Tr_HVAC	Water temperature	RTD sensor	Return temperature – Building HVAC
F_geo	Flow rate	Electromagnetic flow rate meter	Volumetric flow rate – geothermal source
Ts_geo	Water temperature	RTD sensor	Supply temperature – geothermal source
Tr_geo	Water temperature	RTD sensor	Return temperature – geothermal source
F_DHW	Flow rate	Electromagnetic flow rate meter	Volumetric flow rate – DHW
Ts_DHW	Water temperature	RTD sensor	Supply temperature – DHW
Taq	Water temperature	RTD sensor	Temperature from grid for DHW use
PEC	Electric power	Energy analyzer	Compressor electrical power
Paux	Electric power	Energy analyzer	Hydraulic pumps electrical power

Table 16 shows an overview of the characteristics of the probes installed in the pilot site.

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Table 16. Main technical characteristics of the probes

Probe	Model	Technical specifications
Resistance Temperature Detector (RTD)	Tersid MRT	Measuring range: -10°C/120°C 3 wires Accuracy: ± 0.1°C
Digital pressure transmitter	Riels RIB-PA23SX	Measuring range: 1/1000 bar Accuracy: ± 0.25% measuring range Output signal: 4÷20mA - 0÷10V - 0÷5V - 0,5÷4,5V Temperature range: up to 100°C
Magnetic inductive volumetric flow sensor	Sika VMZ.2	Measuring range: 2,5-50 l/min Accuracy: ±0.7 % of reading, ±0.3 % of range Repeatability: ± 1 % Response time: <100 ms
Electrical energy analyser	Energy analyzer Electrex Femto D4	Measuring range: 0-1999 MW (active power) 0-100 GWh (active energy)

The aforementioned parameters are acquired by a datalogger (model AIM-8) which is linked to a gateway (model UCM-316). The gateway is connected via an ethernet cable to the internet network; the collected data are available within a dedicated web platform from which they can be downloaded in the form of .csv file.

The main characteristics of the datalogger as well as of the gateway are shown in *Table 17*.

Table 17. Main characteristics of the acquisition system components

	Datalogger AIM-8	Gateway UCM-316
Power Supply	9-36 Vcc	9-36 Vcc
Power consumption	<10 VA	<10 VA
Dimensions	116x101x33 mm	147x128x50 mm
Weight	170 g	400 g
Interfaces	RS485	RS485
Protocols	Modbus RTU, Modbus TCP/IP	Modbus RTU, Modbus TCP/IP

7.2 R&D campus of IMP in Belgrade, Serbia (demonstration site nº 2):

In this case, the ECHO TES solution tested will count only on a TCMs reactor and a PCM accumulator. Initially, in the proposal the ECHO TES to be installed in Serbia was considered without ice storage, but the possibility to install at least a support strategy for the existing cooling system is under consideration. The demo case consists of a 300 m^2 stand-alone building operating as living lab, with 13 kW_t and 9 kW_e peak consumptions, and estimated yearly heating demand of 8000 kWh, located in the R&D campus of IMP in Belgrade, Serbia (Figure 16). The campus is heated by a local heating plant, running on fuel oil, with, inside the buildings, radiator-based heating (steam and water) system, and cooled by individual AC units.

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Figure 16. Demonstration site No 2 in Belgrade, Serbia

7.2.1 Thermal load assessment

Within IMP campus, the specific, so called 'blue building', will be used as a pilot within ECHO project. This one was, already, described in [3] which, also, covered thermal characterization. Here, a summary of the most relevant points in this regard will be given.

Total thermal energy losses, which are due to heat conduction and convection, are calculated by summing partial heat losses coming from each surface in the building (e.g. walls, windows, roofing, etc.) following the general heat loss equation:

$$L_{losses} = \sum_{i=1}^{N} \left(\frac{\lambda_i A_i}{D_i} + h_i \cdot A_i \right) \cdot (T_{room} - T_{out})$$

where index i is used to denote a particular surface, λ_i represents its thermal conductivity, h_i is its heat transfer coefficient, A_i is its conducting area, D_i is its thickness and T_{out} is the ambient temperature outside the building.

Another feature of buildings is referred to as thermal mass, which represents the ability to store internal energy. In the considered use case, energy is accumulated by the air inside the building (causing the increase of room temperature) as well as by surrounding surfaces, e.g. walls, windows, ceilings, etc., as defined in the following expression:

$$L_{stored} = m_{air} \cdot c_{air} \cdot \Delta T_{room} + \sum_{i=1}^{N} (m_i \cdot c_i) \cdot \Delta T_{room}$$

where again index i is used to denote a particular surface, m_i and m_{air} represent the mass of each building surface and inside air, with their specific heat coefficients c_i and c_{air}, respectively.

Finally, the overall energy balance is derived by splitting the total heat gains into stored energy and total heat losses:

$$\begin{aligned} L(\mathrm{k}) &= L_{losses} + L_{stored} \\ &= m_{air} \cdot c_{air} \Delta T_{room}(\mathrm{k}) + \sum_{i=1}^{N} (m_i \cdot c_i) \cdot \Delta T_{room}(\mathrm{k}) + \sum_{i=1}^{N} \left(\frac{\lambda_i A_i}{D_i} + h_i \cdot A_i \right) \cdot \Delta T_{room}(\mathrm{k}) \end{aligned}$$

Following the presented approach, and taking the values from the Table 18, taken from [3], estimated thermal demand of the pilot site is given in Figure 17 from [3] and hence it could be said that peak thermal demand of the blue building is 13 kWt.

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Table 18. Parameters for building and heat load modelling

Building properties	Walls	Roof	Windows	Air
Area $A_i[\mathrm{m}^2]$	320	601	8	-
Thickness $D_i[\mathrm{m}^2]$	0.2	0.2	0.01	-
Mass $m_i[\mathrm{kg}]$	122880	3846	162	1496
Specific heat $c_i[\mathrm{J\ kg^{-1}K^{-1}}]$	835	835	840	1005
Thermal conductivity $\lambda_i[\mathrm{Wm^{-1}K^{-1}}]$	0.038	0.038	0.78	-
Heat transfer coefficient $h_i[\mathrm{Wm^{-2}K^{-1}}]$	15	9	14	-

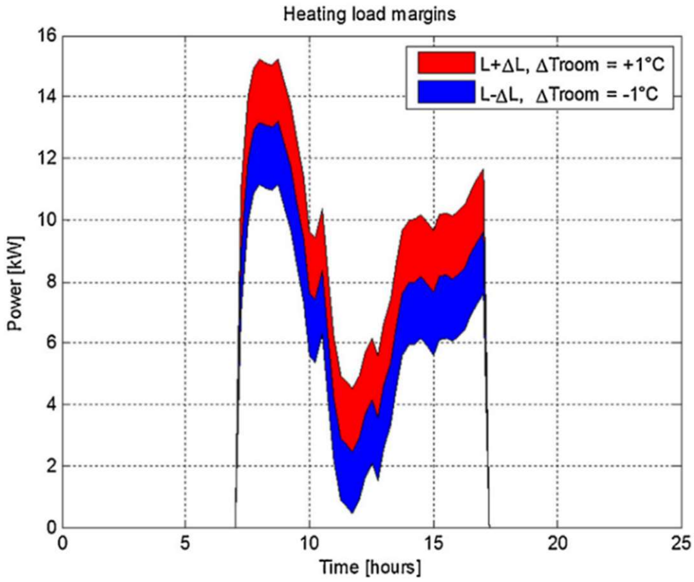

Figure 17. Estimated thermal demand for the blue building

Taking into consideration that this thermal demand exceeds the capacity of the current version of ECHO TSS designed solution, there is the potential of selecting a part of the blue building as the pilot site (e.g. one or couple of offices), in order to match pilot demand and the ECHO system capacity.

7.2.2 Instrumentation and Sensor Deployment

Existing pilot data is collected using a SCADA system, obtaining new data points and integrated with the current solution.

There are a group of existing key data points that are listed behind (*Figure 18*):

- Mazut flow (smaller and bigger tank) and it is calculated based on the mazut level measurement.
- PV production.
- Weather station (insolation, temperature, wind speed, wind direction).
- Temperature of existing heat exchangers.
- Consumption of electrical boilers.

So as part of ECHO TES solution, this key data points should be added (*Figure 19*):

- Heat meters.
- Temperature sensors for newly installed tanks.
- Relative humidity.
- Electric power meters.
- Relative pressure.

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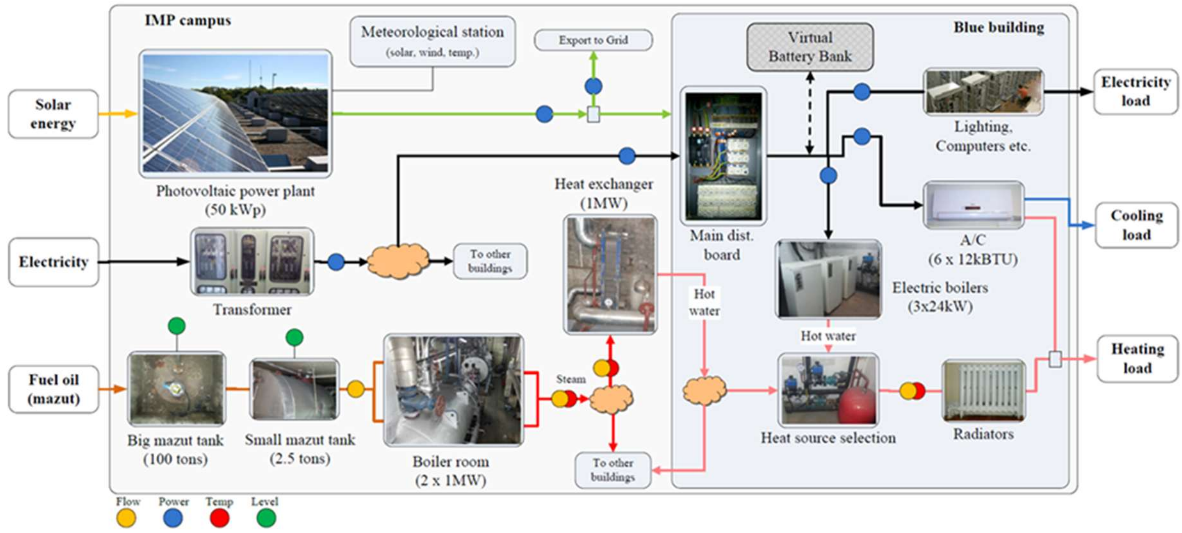

Figure 18. Scheme of the demonstration site No 2 in Belgrade, Serbia

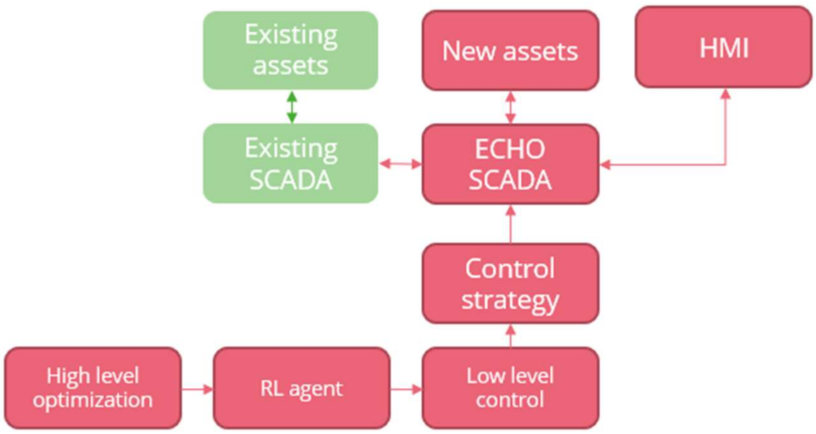

Figure 19. Scheme of the monitoring and management system of demonstration site No 2 in Belgrade, Serbia

7.3 Residential eco house in Putte, Belgium (demonstration site nº 3):

Another complete ECHO TES solution will be tested in this demo case in two buildings at 20 m distance from each other built in 2016, with a total area of 370 m^2. The demo case is composed by a residential eco house and an adjacent vet's office in Putte, Belgium (Figure 20). Both are equipped with radiant floor panels, a geothermal field heat pumps of 12 kW, 6 solar collectors heating up a 300 L sanitary water tank and a 1000 L thermal buffer storage tank. Through a heat exchanger, solar thermal energy is added to the geothermal energy during heating and discharged in the field during cooling.

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Figure 20. Demonstration site No 3 in Putte, Belgium

7.3.1 Thermal load assessment

The heating and cooling system and the photovoltaic plant of demonstration site No 3 will consists of the following components:

- Reversible geothermal heat pump of 12 kW.
- Geothermal field with six borehole heat exchangers (total length 480 m) that all will be connected to the heat pump, in winter and two connected to the heat pump and four to a thermal storage tank of 1000 liter, in summer.
- Six flat bed solar panels connected to hot sanitary water tank and thermal storage tanks.
- Thermal storage tank connected in series with geothermal field supplies energy to heat pump in winter.
- Thermal storage tank recharges the soil in summer.
- Hot sanitary water tank of 300 liter connected to heat pump, solar thermal and an instantaneous preparator.
- Hot/cold storage tank of 200 liter connected to heat pump and supplying radiant panels on first floor, ground floor and the veterinary studio.
- In summer, cold storage tank supplies also dehumidifier.
- Mechanical ventilation in eco house with heat recovery unit.

The heating and cooling demand of the buildings are represented in Tables 19-20.

Table 19. Energy demands of the eco house of demosite No 3 pilot building

Month	Energy Demand (kWh)	
	Heating	Cooling
January	2133.24	0.00
February	1669.79	0.00
March	1276.08	0.00
April	596.34	0.00
May	123.84	49.80
June	0.00	154.53
July	0.00	256.87
August	0.00	145.12
September	91.29	41.57
October	671.06	0.00

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November	1509.08	0.00
December	2034.52	0.00

Table 20. Energy demands of the vet's office of demosite No 3 pilot building

Month	Energy Demand (kWh)	
	Heating	Cooling
January	1098.32	0.00
February	868.78	0.00
March	663.14	0.00
April	333.19	0.00
May	67.40	8.86
June	0.00	36.66
July	0.00	66.78
August	0.00	35.22
September	0.00	20.40
October	283.17	0.00
November	710.89	0.00
December	1019.20	0.00

7.3.2 Instrumentation and Sensor Deployment

The demonstration site No 3 will count with temperature sensors pt100, temperature sensors NTC, electromagnetic flow meters and electrical energy analysers (*Figure 21*).

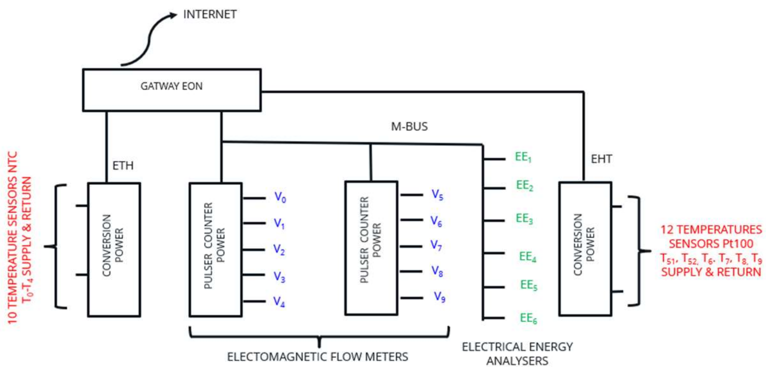

Figure 21. Scheme of the demonstration site No 3 in Putte, Belgium

In *Table 21*, the list of temperature sensors located in the building are described.

Table 21: List of temperature sensors in building

Code	Description	Model	Unit
T0 S	Supply temperature from heat pump to heating/cooling tank	Pt 100	°C
T0 R	Return temperature from heating/cooling tank to heat pump	Pt 100	°C
T1 S	Supply temperature heat pump to geothermal field	Pt 100	°C
T1 R	Return temperature from geothermal field to heat pump	Pt 100	°C
T2 S	Supply temperature from solar tank to heat exchanger	Pt 100	°C

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T2 R	Return temperature from heat exchanger to solar tank	Pt 100	°C
T3 S	Supply temperature from solar collectors to solar/DHW tank	Pt 100	°C
T3 R	Return temperature from solar/DHW tanks to solar collectors	Pt 100	°C
T4 S	Supply temperature from heat pump to DHW tank	Pt 100	°C
T4 R	Supply temperature from DHW tank to heat pump	Pt 100	°C

The list of temperature sensors in geothermal field is shown in *Table 22*.

Table 22: List of temperature sensors in geothermal field

Code	Description	Model	Unit
T5 1 S	Supply temperature heat pump to S1	Pt 100	°C
T5 1 R	Return temperature S1 to heat pump	Pt 100	°C
T5 2 S	Supply temperature heat pump to S2	Pt 100	°C
T5 2 R	Return temperature S2 to heat pump	Pt 100	°C
T6 S	Supply temperature heat pump to S3	Pt 100	°C
T6 R	Return temperature S3 to heat pump	Pt 100	°C
T7 S	Supply temperature heat pump to S4	Pt 100	°C
T7 R	Return temperature S4 to heat pump	Pt 100	°C
T8 S	Supply temperature heat pump to S5	Pt 100	°C
T8 R	Supply temperature S5 to heat pump	Pt 100	°C
T9 S	Supply temperature heat pump to S6	Pt 100	°C
T9 R	Supply temperature S6 to heat pump	Pt 100	°C

The electromagnetic flowmeters used in the demo case are described in *Table 23*.

Table 23: List of electromagnetic flowmeters

Code	Description	Model	Unit
V0	Flow to heating/cooling tank	VMZ153S1PEG14430	l/min
V1	Flow to geothermal field	VMZ204S1PEG14540	l/min
V2	Flow from solar tank through heat exchanger	VMZ204S1PEG14540	l/min
V3	Flow to solar collectors	VMZ204S1PEG14540	l/min
V4	Flow to DHW tank	VMZ204S1PEG14540	l/min
V5	Flow from S1 and S2	VMZ204S1PEG14540	l/min
V6	Flow from S3	VMZ204S1PEG14540	l/min
V7	Flow from S4	VMZ204S1PEG14540	l/min
V8	Flow from S5	VMZ204S1PEG14540	l/min
V9	Flow from S6	VMZ204S1PEG14540	l/min

The list of electrical energy analysers used is shown in *Table 24*.

Table 24: List of electrical energy analysers

Code	Description	Type	Unit
TOTAL	Total consumption house and stables; all three phases	FEMTO D4 70A ECT	Watt
HC_HSW	Consumption heating and cooling; all three phases	FEMTO D4 70A ECT	Watt

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COMPRESSOR	Consumption heat pump compressor; all three phases	FEMTO D4 70A ECT	Watt
PUMP C1	Consumption pump to geothermal fields (winter: all; summer S1/S2)	FEMTO D4 70A ECT	Watt
PUMP C2	Consumption pump to geothermal fields (summer S3/S4/S5/S6)	FEMTO D4 70A ECT	Watt
PUMP HP	Consumption heating/cooling and HSW pumps	FEMTO D4 70A ECT	Watt
PV	Production of photovoltaic panels; all three phases	FEMTO D4 70A ECT	Watt
STUDIO	Consumption stables; all three phases	FEMTO D4 70A ECT	Watt

8 Conclusions

The "D2.2 ECHO TES System and Control Concept" report marks a substantial advancement in the design of TES device, primarily through the establishment of key indicators and the analysis of TES operational parameters.

The development of indicators has been systematically executed to ensure comprehensive monitoring and evaluation of the results of the democases. Each indicator has been meticulously defined, with its typology, either quantitative or qualitative, clearly delineated. The phases of the project during which these indicators are assessed have been identified, alongside the specific deliverables where evaluation results will be documented. This structured approach facilitates a rigorous and consistent assessment framework, enabling stakeholders to gauge the project's progress and effectiveness in achieving its objectives.

The identification and definition of TES device parameters represent a key first step in configuring operational parameters. A range of expected values for operational parameters for TES device is presented, providing a more detailed and comprehensive understanding of their performance and capabilities. Furthermore, the report sets the stage for upcoming demonstration case studies, emphasizing the need to include comprehensive sensor equipment details in its final phase, starting from those already existing and completing them.

Moving forward, with Internal Key Indicators (IKIs) for phases of the project now identified and defined, there will be a focused effort during Task T2.5 to implementation and monitor these indicators. This task is crucial as it involves identifying potential risks and barriers while conducting the initial preliminary analyses. The systematic tracking and analysis of these IKIs in Task 2.5 are pivotal, ensuring that any emergent challenges are swiftly identified and addressed, thereby reinforcing the project's approach to achieving its outlined goals.

References

[1] Draft of ECHO project deliverable D3.2: Selection of PCMs for the PCMs accumulators in the TCMs TES solution

[2] Draft of ECHO project deliverable D3.4: Selection of eutectic PCM and optimization of cooling unit

[3] M. Batić, N. Tomašević, G. Beccuti, T. Demiray, and S. Vraneš, "Combined energy hub optimisation and demand side management for buildings," *Energy Build*, vol. 127, pp. 229–241, Sep. 2016, doi: 10.1016/J.ENBUILD.2016.05.087.

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