HYSTORE
Hybrid Services from Advanced Thermal Energy Storage Systems

WP – 1 Use cases and framework scenario identification

Task 1.2 KPI-driven approach for assessment of technologies and pilot operation

D 1.2 KPI analysis of technologies and pilots' operations

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DISCLAIMER

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Table 1 Project and funding information

Project	
Project Acronym	HYSTORE
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Deliverable title	KPI analysis of technologies and pilots' operations
Description	The main objective of this task is to provide quantitative measurement of the performances of the HYSTORE technologies and combined systems during their operational phase. The KPI panel will include indicators to consider the two levels of integration provided by the project's tools: the integration with existing grid/utilities and the integration at end-user level with specific parameter ad-hoc developed. The different KPIs to be proposed will deal with the following aspects: energy characteristics (power capacity, storage capacities, etc.), energy efficiency (instantaneous and integrated energy yield, primary energy consumption, self-consumption, and self-sufficiency, etc.), cost efficiency (e.g., energy bill cost, investment, maintenance costs, ROI, LCOE, etc.), impact on electric and thermal networks (e.g., contemporaneity demand-generation), spatial efficiency (Compactness, spatial constraints), impact on comfort (conditions of use and maintenance, thermal comfort impact characterization), environmental impact (life cycle considerations, share of renewable energy, CO_{2eq} emission, embodied energy, etc.), robustness, reliability, autonomy. A complete list of KPIs will be provided together with the set of equations needed for their calculation and to include in the HYSTORE platform. All the KPIs will be used for benchmarking during lab-testing of the solutions in WP3/WP4 and for the demonstration activities in WP6.
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Executive Summary

Energy storage technologies can play an important role in decarbonising the energy system and creating a highly flexible energy system. The HYSTORE project is intending to overcome several challenges through a multidisciplinary set of solutions with utilisation and implementation of innovative TES solutions. To address the current challenges in the thermal energy storage market, HYSTORE will develop and validate an innovative set of TES concepts, based on the combination of cutting-edge technology components. , It also promotes TES as an enabler to enhance the flexible and reliable operation of building both power and thermal systems as decentralised energy resources, exploiting the increasing share of renewables, context maximising the exploitation and harnessing local RES generation and electrical grid peak load shedding and management. Regarding cost-effectiveness, the aim of HYSTORE is to increase system efficiency by up to 20 % and an average reduction of 50 % in CAPEX and 10 % in OPEX. During the project, the HYSTORE's solutions will be implemented across four demonstration sites in four representative climates classified according to Köppen Geiger classification [1] (Spain (Csa), Austria (Cfb), Sweden (Dfb), and Ireland (Cfb)), with special consideration to their cost effectiveness and potential replicability and scalability to fulfil the main HYSTORE objectives. The main objective of this deliverable is to provide a list of Key Performance Indicators (KPIs) and mathematical calculation methods to be utilised during the operational phase of the HYSTORE demonstration sites to facilitate quantitative measurement of the performances of the HYSTORE technologies and solutions. This document is structured as follows:

- **Section 1 Introduction** describes the scope of the report and general context of the project.
- **Section 2 Methodology** overviews the methodology and procedure used to define the KPIs. Additionally, it details the HYSTORE use cases and TES technologies, as well as the system layout, the nomenclature, and abbreviations used in this report.
- **Section 3 KPIs definition** presents a list of the key performance indicators (KPIs) under which the HYSTORE technologies effectiveness should be evaluated and is classified into five main domains of technology KPIs, energy KPIs, economic KPIs, environmental KPIs, and social KPIs.
- **Chapter 4 KPIs calculation methods** outlines the definition of the equations required for calculation of each indicator to be used in the operative phase and included in the HYSTORE platform. For each KPI, units of measurement and mathematic definition has been defined in this section.
- **Chapter 5** provide a summary of the deliverable.
- **Chapter 6** lists the references utilised in the document.

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1. Introduction

Key performance indicators (KPIs) are essential metrics utilised for analysing and optimising the operation in any project. Accurate definition of such KPIs can facilitate performance evaluation of the overall project and to assure that all utilised technologies are performing efficiently. Key performance indicators (KPIs) are widely utilised for performance measurement of projects and activities to achieve specific and strategic goals. KPIs are widely utilised in business and financial assessments [2] and can give broad insights into the technical, economic, environmental, and social aspects of projects. KPIs can be classified in five categories as stated by Cabeza et al. [2].

1. Quantitative vs. qualitative indicators, which could be measured by giving a magnitude value or an adjective without scale.
2. Leading and lagging indicators, which are used to predict the outcome of a process or present the accomplishment or failure post hoc.
3. Input process and output indicators, which measure the number of resources consumed during the generation of the outcome. They represent the efficiency of the production of the process or reflect the outcome of the process activities.
4. Directional indicators, which can track the performance of a technology and/or application towards improvement.
5. Financial indicators, that consider the economic aspects of a technology, application etc.

The application of KPIs have been investigated for various applications. For example, Kourkoumpas et al. [3] reviewed key KPIs which can be used for environmental and energy performance assessment and evaluation of energy storage solution incorporated into the renewable energy systems. In another study, Li et al. [4] proposed a systematic approach to identify KPIs and stakeholders for multi-level energy management, at both the district and the building scales. In a recent study authored by Li et al. [5] a comprehensive review was carried out to identify key data-driven KPIs which could be used for building energy flexibility assessment. Furthermore, with regard to the design, development, modelling, implementation, application, and assessment of advanced and novel thermal energy storage systems, Palomba and Frazzica [6], and Cabeza et al. [2] proposed various KPIs which could be used for the analysis of thermal energy storage technologies.

The main objective of this document and HYSTORE's Task 1.2 is to list the most important KPIs that will be utilised during the operational phase of the HYSTORE project and facilitate quantitative assessment of the performances of different technologies provided by the HYSTORE partners, technology providers, and stakeholders. The proposed KPIs will include indicators to consider the standalone and combined performance of each technology implemented in HYSTORE project, and the overall impact of the innovative solutions on the thermal and electricity networks from energy, economic, environmental, and social perspectives. A comprehensive set of KPIs will be proposed which will be used to assess different techno-economic aspects of the HYSTORE technologies and pilots which are listed as followings:

- Energy characteristics (energy production efficiencies, storage densities, temperature levels, etc.)
- Energy network efficiency (primary energy consumption, self-consumption, self-sufficiency, etc.)
- Cost efficiency (e.g., energy bill cost, investment, maintenance costs, PBP, ROI, LCOE, etc.)
- Spatial efficiency (compactness, spatial constraints)
- Environmental impact (life cycle considerations, renewable energy shares, CO_{2eq} emission, embodied energy, etc.)
- Reliability, robustness, and autonomy (loss of load probability, etc.)
- Impact on comfort (conditions of use and maintenance, thermal comfort impact characterisation)

A complete list of KPIs will be provided together with the set of equations required for the calculation of KPIs and to include in the HYSTORE platform.

2. Methodology

2.1. Overview

In this section the methodology that has been used for the KPIs definition for both technologies and overall system level is described. To define the KPI selection methodology the first step was to identify and list the main objectives, scopes, and stakeholders of the project. Afterwards, a comprehensive literature review was carried out to find out the most relevant scientific articles relevant to the KPI definition in energy systems and specifically thermal energy storage systems. Furthermore, projects reports and information available of other EU projects were reviewed to structure a clear roadmap for KPI definition in the HYSTORE project. In the next step the main technological advancements of the project were defined and classified based on their application for each use case and demonstration site.

To define the main KPIs relevant to the HYSTORE project a collaborative and iterative approach was adopted to leverage on the technical insights and expertise dispersed in the project consortium and involved stakeholder.

A questionnaire was circulated to the technology providers, tool developers and demo leaders, where they were asked to provide suggestions on the relevant indicators that can be utilised to monitor and assess the performance/functionalities of the innovative thermal energy storage systems and ICT tools technologies implemented in the HYSTORE project.

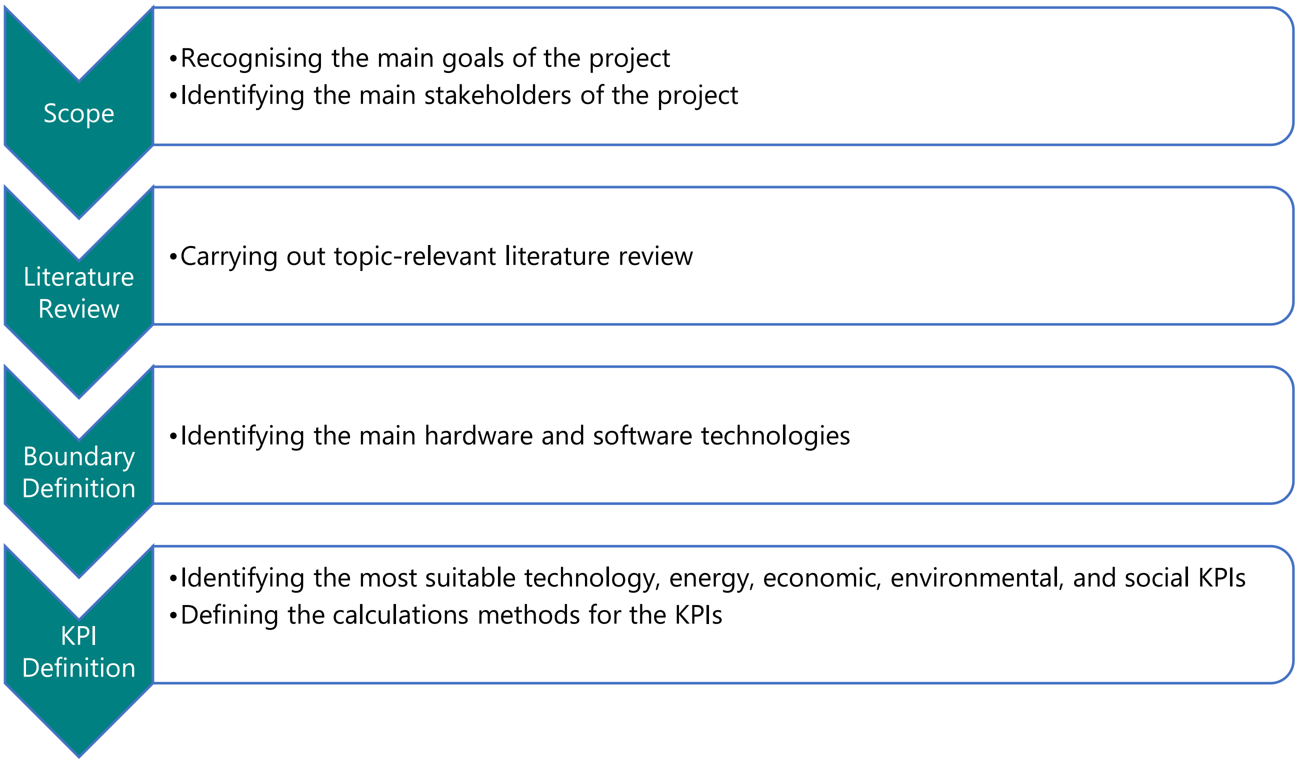

Figure 1 KPIs identification procedure workflow.

The suggested KPIs were discussed in multiple sessions with the HYSTORE pilot leaders all the partners involved in each use case (UC). The group members, relative technologies and main demonstration objectives are summarised in **Table 3**. Then the most relevant KPIs were selected according to the preference and necessity of the technology providers and pilot leaders.

Table 3 A summary of use cases (UC), and key enabling technologies (KET).

#	Use Case name	Partners	KETs involved	Demonstration objectives
UC 1	Non-DHC connected multi-purpose building (Langenwang, Austria)	**PINK**, OCHS, AIT,	• Compact plate-fin Refrigerant-PCM-Water-heat exchangers (RPW-HEX) with Heat pump (HP) developed by (AIT, OCHS, PINK, RAAL)	**Integration of ALL-IN-ONE PCM solution** and services provision from non-DHC connected building. Integrating a PCM thermal storage system for multi-purpose use in buildings for heating, cooling and DHW generation.
UC 2	KTH Live-in-Lab, non-DHC connected (Stockholm, Sweden)	**KTH**, MASTON, STAM, UCD, DCU	• PCM latent heat TES tank with heat pump (KTH, RUBI)	**Integration of HEATING PCM solution** and services provision from residential community (KTH campus). It consists of an LHTES combined with a heat pump and is specifically suited for heating-driven climates. Different possible integrations with the heat pumps will be evaluated
UC 3	Montserrat building complex with DHC (Montserrat, Spain)	**CRM** ARC, SOR, CNR, RUBI, MASTON	• Low-temp PCM heating and cooling solution (AIT, RUBI, KTH) • TES Storage based on sorption and chemical reactions	**Integration of LOW-TEMP HEATING & COOLING PCM solution** which is a short-term storage mainly intended for cooling dominant climates. It is intended for connection with the heat pumps. **Integration of COOLING TCM solution** and hybrid (energy and power) services provision from DHC-connected to a heterogenous (residential and services buildings) complex.
UC 4	UCD Belfield Campus with DH (Dublin, Ireland)	**UCD** MASTON, STAM, DCU	• TES Storage based on sorption and chemical reactions (TCM storage) that will be developed by (CNR, SOR, INOVA)	**Integration of TCM HEATING&COOLING solution** and hybrid (energy and power) services provision for a heterogenous (residential and services buildings) complex (Clustered building sharing thermal and electrical network). It consists of a sorption storage and will be suitable for storing energy and then allowing for heating or cooling provision according to a flexible operating mode.

2.2. Use Cases

In the HYSTORE project there are **four demonstration sites** which are in four different countries and climate classification with different technology installations. A brief description of each use case is given in this section.

2.2.1. Use Case 1: Non-DHC connected multi-purpose building (Austria)

This demonstration site is located close to the Semmering mountain at the eastern end of the Alps within the valley of the River Mürz it's an old building built around 1960s where no major retrofit was carried out. The existing energy system installed in the building is partly using fan coil - heaters and an underfloor heating system. The offices are currently using high temperature radiators, combined with heated ceiling to cover peak loads. Both are already controlled by thermostatic valve using a daily and weekly time program for the temperature settings. The office area is equipped with a cooling ceiling to improve the comfort during summer. The is also a solar PV plant with 6,2kWp, solar thermal plant installation situated at the tower surface to warm up the water for the pressure test of the tanks produced. This plant is not coupled to the buildings heating system.

2.2.2. Use Case 2: Block of buildings connected to heat pump groups generation (Sweden)

KTH Live-in-Lab is a 'full-scale test environment' consisting of three testbeds: Testbed Akademiska Hus, Testbed Einar Mattsson (Testbed EM) and Testbed KTH. They are all real environments having real users living and working inside the environments, combined with physical and digital infrastructure for the testing of everything from systems and sensors to user behaviour and management. In this project, KTH will use the Testbed KTH, which is a 300 m2 innovation arena which can be remodelled to accommodate the needs of the research engagements. For instance, this Testbed KTH currently (by 2022 Spring) is operated as a single co-living unit for four students. Prior to that, this was operated as 4 studio apartments in the same arena. This Testbed KTH is located within the Testbed EM: a set of three buildings with a total of 305 student accommodations. Space heating system is either provided by a central group of three 64 kW heat pumps or by a smaller and dedicated heat pump with a nominal power of 12 kW connected to an HVAC system which supplies pre-heated air to the apartment. Domestic hot water is currently delivered from Testbed EM, generated by heat pumps. Free cooling can be provided by using the heat pump installation in Testbed EM. This makes the Live-in-lab a perfect environment to test the HYSTORE solutions that are intended for the connection with heat pumps. Currently there is a solar PV system with 150 kW nominal capacity with a battery of 366 kWh and renewable heat from ground-source/borehole heat pump. HYSTORE platform and advanced data analytics will test local aggregation potential, for TES acting as key enablers for then coupling between the geothermal thermal systems and energy networks. It enables, for example, the provision of demand side flexibility from the thermal capacity of the pilot when needed or tailored demand response programs.

2.2.3. Use Case 3: DHC-connected district with multi-purpose buildings (Spain)

Montserrat is a mountain massif in Northern Spain, located 20 km from Barcelona. The Abbey of Montserrat is organized as a small town that has diverse uses, residential, hotel, restaurant, shops, museums, offices, school, etc. As a result, it is organized as a large network of buildings with different schedules and profiles, which lead to different energy needs, but with centralised management from the Central Management Service. The current installation is as micro DHC network that covers the high heating and cooling demands of the Montserrat building complex, impelled by a biomass plant of 2.5 MW. The final aim is to remove completely the use of fossil fuel (propane) to cover peak load heating and cooling demands and minimize towards zero the environmental impact of the Montserrat historical building complex. The TES and HYSTORE smart operation platform acts as key enablers for then thermal-electrical coupling between the DHC and electrical grid, enabling for example the provision of demand side flexibility from the thermal capacity of the pilot when needed.

2.2.4. Use Case 4: University campus with local RES and proprietary DH (Ireland)

Belfield is the primary campus from University College Dublin with approximately 30,000 daily population. The UCD Belfield Campus is like a small city. CD has a total of 3.4 MWe of on-site CHP. The electricity is used on-campus, the heat is used for the Belfield District Heating System which is used for space heating and Domestic Hot Water. In addition, 2 gas boilers for a total capacity of 3.2 MW are installed, as well as a biomass boiler, and a 1MW High Temperature heat pump. This heat pump will act as a low carbon heat generator and will displace gas boiler heat over the coming years. There is currently ~500kW nominal capacity of solar PV installed on UCD buildings. The UCD Campus is served with a large-scale central Building Management System (BMS). This Cylon BMS system is used to centrally control all HVAC, water, and lighting services on campus. The system is deployed throughout the entire campus and is a key tool for implementing energy and carbon optimisation measures.

Figure 2 shows a summary of HYSTORE's four different pilots and TES technologies involved in each use case.

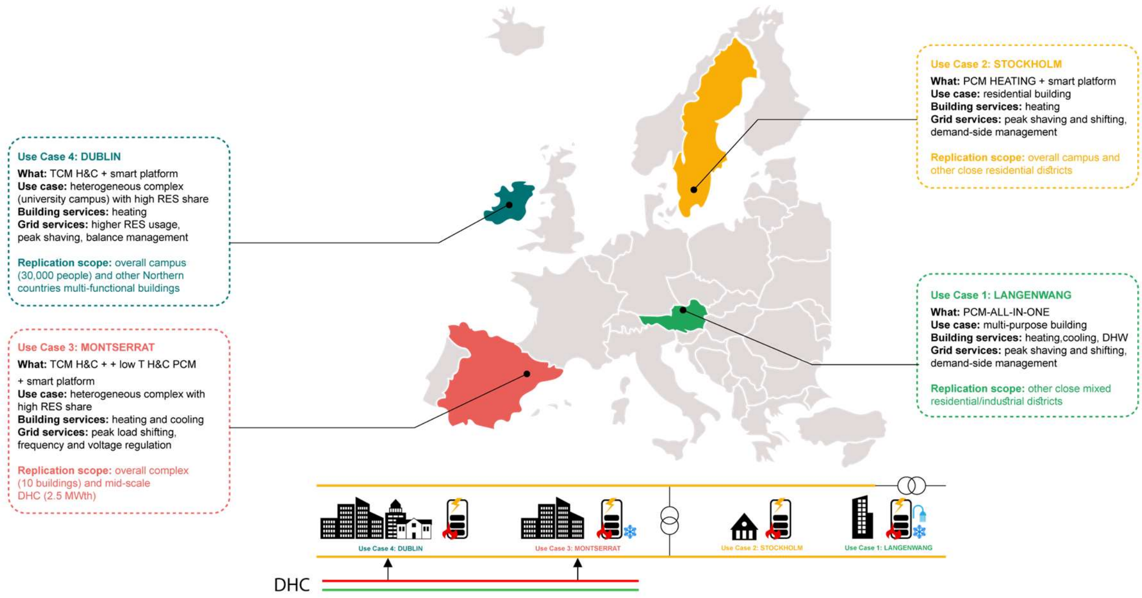

Figure 2 A summary of the HYSTORE use cases, geographical locations, and TES technologies.

2.3. HYSTORE TES-enabled energy systems solutions

2.3.1. ALL-IN-ONE PCM solution for heating, cooling and DHW

It is a modular high-performance PCM storage device for multi-purpose use in buildings. It can be used for heating, cooling and DHW generation. With a typical charging power of 2-3 kW_{th} and a charging time of about 2-4 hours, it can meet the daily DHW need for a family and provide heating or cooling energy of about 4-12 kWh_{th} when fully charged. PCM ALL-IN-ONE solution consists of (see Figure 3): a high performance PCM storage with aluminium Micro/Multi Port Extrusion (MPE) tubes for the water and refrigerant; a small scale heat pump (HP) using the natural refrigerant Propane (GWP=3), a hydraulic group (for thermal discharging) consisting of a circulation pump, valves, energy meters and a plate-type heat exchanger acting as a hydraulic separator to the heating/cooling network or for direct DHW integration. The core of the solution is the so-called Refrigerant-PCM-Water-heat exchangers (RPW-HEX). A first version of such HEX was developed by AIT and OCHS in the H2020 HYBUILD project [7], however, it showed high performance but low volumetric energy density. A new adapted design with MPE tubes and aluminium fins has been developed and tested in the national Austrian research project CHALLENGE, however only for hot gas utilisation and condensation (heating purposes), but not for evaporation (cooling purposes). Furthermore, the full-scale RPW-HEX is designed for the refrigerant R32 with a GWP of 675.

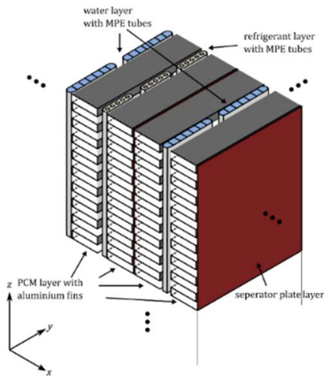

Figure 3 The RPW-HEX under development in challenge.

In HYSTORE, a full scale RPW-HEX should be designed for heating and cooling to be used with the natural refrigerant Propane. The total weight of one box should not exceed 150-200 kg to ensure easy handling for workers and to allow for retrofits. To ensure a long lifetime of the storage, the PCM will be easily replaceable should degradation effects in the PCM reduce the performance after many years of operation. This option means also that the entire storage tank can continue to be used if the boundary conditions in the building change over time. **Figure 4** shows different possibilities of integration in buildings.

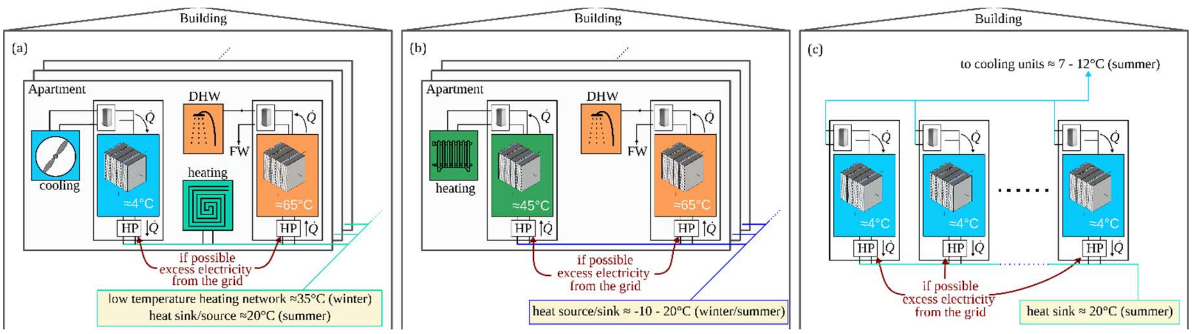

Figure 4: Exemplary integration of the ALL-IN-ONE PCM solution in a building. (a) decentralised storage for cooling and DHW generation for integration in a centralized low temperature heating network, (b) decentralised stand-alone storage-system for heating/DHW and integration into a low temperature anergy-network (District heating network or hydraulic connection to renewable heat source), (c) centralised cooling storage with gradual adjustment to the available excess power from the electric grid.

2.3.2.PCM LOW-TEMP HEATING & COOLING SOLUTION

The low-temp heating and cooling solution is a PCM-based short-term storage mainly intended for cooling-driven climates, that can however supply also low-temperature heating (until 45°C). It is intended for connection with the heat pumps and is based on a modularly designed latent heat thermal energy storage (LHTES) that is currently being developed at RUBI. All the components are mostly polymer-based and as many raw material components as possible will be bio-based. The pictures of the prototypes that have been tested so far at Rubitherm [8]. (about 30kWh and 6kWh storage capacity, depending on the PCM) are shown in **Figure 5**. Innovations developed within HYSTORE will be regarding: (1) the PCM material, since further focus will be put on long-term stability of the PCM by integration of separation inhibitors into the storage. Testing at KTH in large scale will be used to characterize and validate the PCM selection. (2) Storage design. Design parameters such the optimum length of one capillary matrix and surface to volume ratio will be optimised to reduce the size of the storage. (3) Modularity. A standard module will be derived that can be connected in series or parallel. Experimental and numerical activities will be carried out at RUBI to validate the effects of upscaling. The use of a standard module, needing only two connections with the heat pump, will also facilitate installation and integration inside the building.

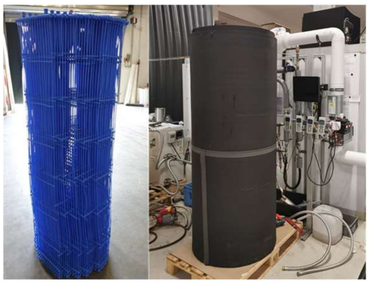

Figure 5: 600 l storage tank with capillary plastic HEX (left),

2.3.3.PCM Heating solution

The HYSTORE PCM heating solution consists of a LHTES combined with a heat pump and is specifically suited for heating-dominant climates. It consists of a stainless-steel PCM storage tank, which will be respectively analysed for using macro-encapsulated PCM immersed in heat transfer fluid (HTF) and a HTF copper spiral coil immersed in PCM, and specifically optimised for the integration with heat pumps. The design will start from a 19-kWh storage already tested in lab-scale by KTH within a recently completed project[1,] which is shown in **Figure 6** . Different possible integrations with the heat pumps will be evaluated, considering the cases of ground-source and air-source systems respectively, and thus making the solution feasible for a wide range of new or retrofitting installations. Within HYSTORE, several improvements are foreseen. Materials: In choosing the specific PCMs, high volumetric storage density will be a priority criterion, followed by robustness and stability at extensive cycling, cost-effectiveness as well as e.g., renewable versus non-renewable origins.

Figure 6: The prototype of PCM heating solution developed at KTH.

[1] Xu, T., Chiu, J. N., Palm, B., & Sawalha, S. (2019). Experimental investigation on cylindrically macro-encapsulated latent heat storage for space heating applications. Energy Conversion and Management , 182 , 166–177.

Figure 7 shows a schematic of possible system integration with the PCM heating solution technology developed in the HYSTORE project.

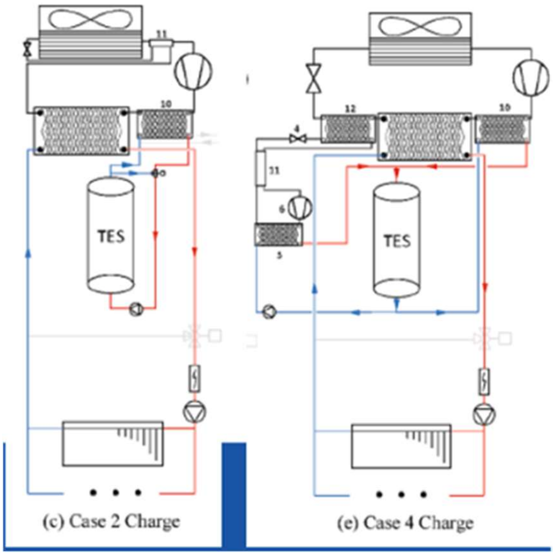

Figure 7: PCM heating solution, evaluation of possible layout for connection with the heat pumps

2.3.4. TCM HEATING & COOLING SOLUTION

The TCM heating and cooling solution developed within HYSTORE project consists of a sorption storage and will be suitable for storing energy and then allowing for heating or cooling provision according to a flexible operating mode. The use of sorption technology for the storage with water as refrigerant. The storage will be designed keeping in mind, as primary goal, cost, and complexity reduction, which are the main issues of such systems. Cost reduction will be achieved by using cheap material (e. g. zeolite Na-Y or 13X with cost <5 €/kg and that are widely abundant and easily sourced in the EU). To make the system with cheap material competitive with SoA research systems, a novel charging system will be put in place, designed, and manufactured by INOVA and consisting of a high efficiency radiofrequency heater, that will allow a homogeneous heating (up to 130°C) in the desired volume.

The heater will consist of a RF generator feeding one pair (or more pairs) of electrodes properly designed to deliver the electromagnetic energy to the chosen sorbent volume: due to the high voltage needed in such a process (in the kV range) the design of the electrodes will allow the uniform delivering of energy avoiding the risk of electric discharge; moreover, with the aim of minimizing the size of the electrical components used to match the electrical impedance of the system, the size of the heated volume and the electrodes layout will be considered during the design of the RF-heater.

Moreover, an innovative configuration will be employed, in which the heat exchanger needed for the discharge of the system towards the heating/cooling distribution of the building is in contact only with part of the storage material. This allows the use of compact and high efficiency HEXs, reducing the cost needed compared to the case of a HEX that should be in contact with a high mass of storage material. Such a configuration is currently under development at CNR within the on-going H2020 HYPERGRYD project. The schematics for the TCM HEATING and COOLING solution is shown in **Figure 8**.

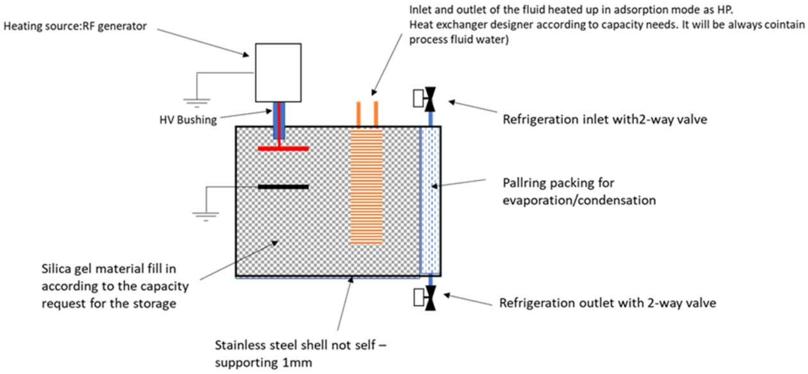

Figure 8: Schematic layout of the TCM HEATING&COOLING solution.

Dedicated engineering activities will be carried out to design a hydraulic group (for thermal discharging) consisting of a circulation pump, valves, energy meters and a plate-type heat exchanger acting as a hydraulic separator that will be integrated within the storage, thus allowing direct connection to the heating/cooling distribution system, facilitating the installation, and reducing the system complexity and installation time.

2.3.5.HYSTORE ICT tools

In this section a brief description of the HYSTORE ICT tools and platforms is given. The overall aim of these tools is to create an interoperable and smart energy systems and services that can facilitate an optimum use of thermal energy systems and thermal-electric grid. One of the main goals of the HYSTORE project is to integrate hardware and software solutions developed seamlessly with the building heating/cooling distribution system, with its energy management and within grid and community level.

2.4. Energy System boundaries definition

In this section a generic energy system layout is defined for the HYSTORE demonstration sites. Each demo site is characterised by a unique network layout. The nomenclature utilised in this report refers to a general energy system layout.

- External energy plant or network
- Connection point to the external grid
- Internal electrical/thermal/combined energy sources
- Thermal energy storage devices
- Utility buildings and services

Figure 9 shows the energy flow and the integrated energy system nomenclature details which will be used in this report. All terms used in Figure 9 are described in detail below. The energy systems studied for the HYSTORE project consist of electricity, heat (thermal), networks, that can have multiple interconnections. The subscripts el and th are used in the KPIs that stand for the electrical and thermal grids, respectively.

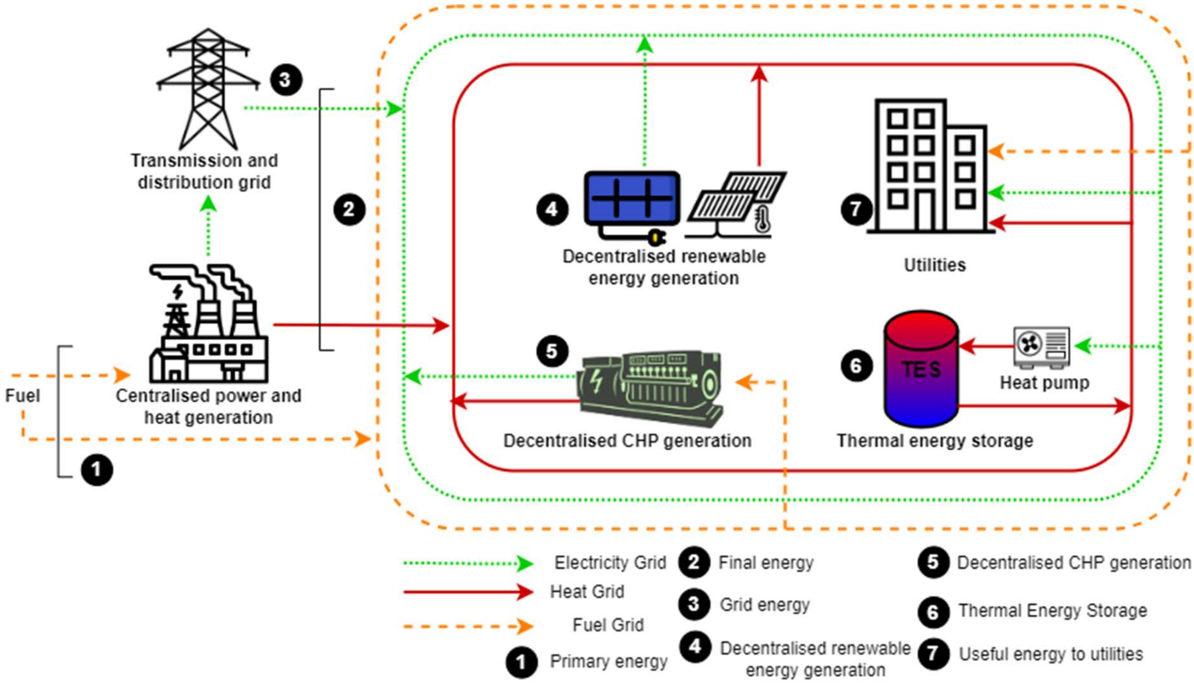

Figure 9 General energy system layout

- **Primary energy (PE)** refers to the total energy contained in raw fuels or waste, used by both external, and internal generation units. This includes the primary energy associated to any fuel or renewable source used for internal and external production, calculated using the country-specific primary energy factors for each specific fuel considered (PEF).
- **Final energy (FE)** refers to the total energy consumed by the system in form of fuel, electricity, or heat.
- **Grid energy (GE)** refers to the energy flowing to the system from the external grid ($GEin$) or to the grid from the system ($GEout$).
- **Decentralised renewable generated energy (IE)** refers to the energy generated locally by internal sources (renewable or non-renewable).
- **Thermal energy storage (stored energy) (SE)** refers to the energy flowing in ($SEch$) or out ($SEdis$) of the storage devices.
- **Useful energy (UE)** refers to the energy received and consumed by the local community.

Since the purpose of HYSTORE project is to develop a set of innovative technical solutions based on the thermal energy storage to improve the overall energy networks, a baseline-future-variation scheme has been utilised for the most proposed KPIs, to evaluate the improvements generated by the HYSTORE project solutions.

- **Baseline ($base$)** scenario refers to the status before the application of HYSTORE's solutions. Required data can be taken from historical measurements available from the HYSTORE demonstration sites or defined ad-hoc for the specific case.

- **Future (fut) scenario** refers to the scenario after the implementation of HYSTORES's technologies and tools. This data can be acquired form the the results of simulations and optimisations, or directly measured on the installed and operating technologies, tools.
- **Variation (var)** refers to any improvement / change of the Future Scenario with respect to the Base Scenario.

Moreover, some indicators require a distinction between renewable or non-renewable sources, or between internal and external network. In such cases, the following subscripts are utilised:

- Renewable sources are identified by the subscript res
- Internal devices or energy flows are indicated with the subscript int

A holistic overview of the HYSTORE ICT tools for control, management, platform and integration and their correlations for interoperability is demonstrated in Figure 10**Figure 10**. The most relevant KPIs which could be used to evaluate the performance of HYSTORE's ICT tools and platforms are described in detail in Section 4.

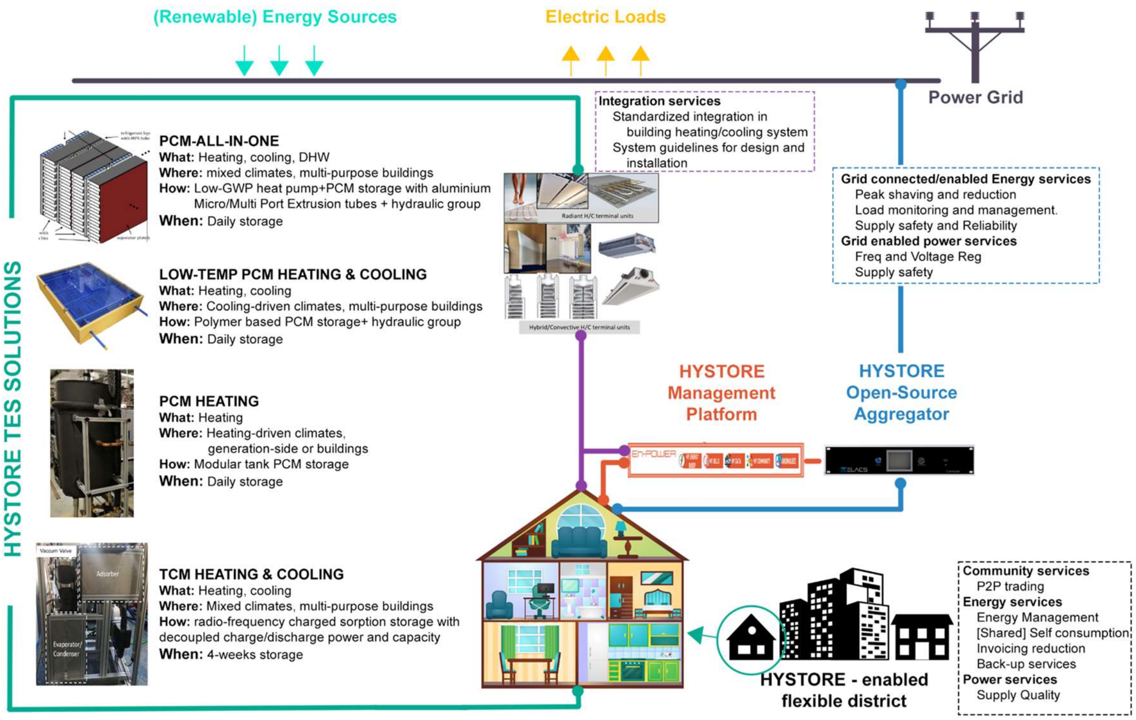

Figure 10: A holistic overview of the HYSTORE hardware and software solutions

3. KPIs definition

Table 4 lists the minimum data set of measured parameters required to evaluate the KPIs and the performances of the HYSTORE technologies. Also, this data can be acquired from the existing smart meters and historical data available from the HYSTORE demonstration sites.

Table 4 Recommended measure parameters for the HYSTORE project,; hr= hour, min= minute, adopted from [9].

	Parameter	Unit	Sensor / Meter	Timesteps	Notes
Consumption	Total consumption of fuels	[kWh]	Fuel meter	hr, min	e. g. biomass, gas for the CHP plant
	Total consumption of district heating / cooling	[kWh]	Thermal meter	hr, min	-
	Total consumption of electricity	[kWh]	Electric meter	hr, min	-
	Total consumption of water	[m^3]	Water meter	hr, min	-
Weather data	Outdoor air temperature	[°C]	Weather station	hr, min	Metered weather data or data from other weather data providers
	Outdoor relative humidity	[%]	Weather station	hr, min	-
	Global irradiation	[W/m^2]	Weather station	hr, min	-
Indoor	Indoor temperature	[°C]	Temperature probe	hr, min	-
	Indoor relative humidity	[%]	Hygrometer	hr, min	
Smart meter / data	Temperature of main water circuits	[°C]	Temperature probe	hr, min	
	Supply air temperature of AHUs, if applicable	[°C]	Temperature probe	hr, min	Only if supply air is thermodynamically treated
	Supply air relative humidity of main AHUs, if applicable	[%]	Hygrometer	hr, min	Only if supply air is humidified / dehumidified

Timesteps required for data analysis, modelling, simulation, visualisation, and other tasks will commonly include:
Monthly/weekly data: typically used for consumptions;
Daily data: provide much richer information as different day types can be distinguished. (workday/weekend/holiday);
Hourly data: typically used for indoor supply air temperature, humidity, solar radiation etc.
Sub-hourly data: typically used for either indoor air temperature, humidity, solar radiation, electricity/heat demand etc. [9].

To calculate a correct building performance, weather data as outdoor temperature, outdoor relative humidity and irradiation must be either measured or collected form the smart data. To evaluate the different impacts of the HYSTORE demonstration projects on track, a set of key performance indicators (KPIs) have been defined.

Since the HYSTORE project aims to bring to the market affordable technologies, monitoring the performance of the different demonstrators is essential in evaluating the transfer, replication, and scalability potential in different European regions. Therefore, relevant economic, energetic, environmental, and social performance indicators (KPIs) will be identified.

To identify the required KPIs for the project's demonstration sites, an appropriate methodology encompassing different working phases has been developed as described below:

- **Analysis of the concept of each use case:** each demo site responsible partner should be interviewed to gather specific information on the objectives and technologies of the demo site, on the specific HVAV system, and heating and cooling needs to achieve the main objectives. Moreover, it is essential to know how the HYSTORE TES and ICT solutions will be integrated with the existing facilities, and thermal/electric network as well as the smart meters etc.
- **Definition of the baseline situation:** the baseline or reference should be identified for each demonstrator to define a reference scenario toward which to compare the situation after the implementation of the HYSTORE technologies.
- **Definition of a list of specific KPIs:** a list of specific technical, environmental, economic and social KPIs has to be identified in order to ensure the convergence of the elaborated list to the real implemented project and to the specific context;
- **Definition of common methodology for calculation of specific KPIs:** a common nomenclature scheme must be setup for the defined KPIs to harmonise the identification of the specific KPIs.

For each use case four main categories of specific indicators are identified:

1. **Technology KPIs**, aimed at evaluating the hardware and software technologies that will be used at the HYSTORE demonstration sites, including the thermal energy storage systems.
2. **Energy KPIs,** aimed at assessing the energy efficiency of the demo sites and technology package during the operation; and
3. **Economic indicators**, providing the evaluation of the economic impact for the involved stakeholders and main end-users;

All KPIs utilised in this project are listed in Sections 3.1 to 3.3 which can be distinguished by unique ID codes and progressive numbers. KPI types are indexed by TECH, EN, and ECO, which stand for Technology, Energy, and Economic, respectively. It should be noted that most of the required KPIs for this project are already exist in the literature and are widely used in the technical reports and European projects [9–11], and the literature [6]. In this project we have utilised the most relevant KPIs to the HYSTORE hardware and software solutions which are listed in Table 5 to Table 7.

In addition, it should be noted that the necessity of utilisation of the proposed KPIs for each specific use case might vary in the next phases of the project depending on various constraints and situations, and some KPIs might not be deemed feasible to be used in the next implementation stages of the project. In the latter stage of the project, and as the project progresses, each use case will be evaluated separately and the most appropriate KPIs will be selected.

3.1. Technology KPIs

This section lists the main KPIs which can be utilised to supervise and analyse the performance of different individual systems and technologies which will be used in the HYSTORE project.

Table 5 Technology (TECH) KPIs for different use cases.

UC[2]	Technology/Tool	KPI	Index	Symbol	UoM	D/O[3]
UC1 (Langenwang, Austria) & UC2 (KTH Live-in-Lab, Sweden)	Modular heat pump	COP heating	TECH 1.1	COP_{heat}	-	O
		COP cooling	TECH 1.2	COP_{cool}	-	O
		COP DHW with PCM losses	TECH 1.3	COP_{DWH}	-	O
		COP DHW without PCM losses	TECH 1.4	COP_{PCM}	-	O
UC1 (Langenwang, Austria) & UC2 (KTH Live-in-Lab, Sweden)	PCM thermal storage	Degree of compactness	TECH 2.1	Φ_{PCM}	-	D
		Energy storage capacity	TECH 2.2	ESC_{PCM}	kWh	D/O
		Energy storage density	TECH 2.3	ESD_{PCM}	kWh/m³	D/O
		Energy storage efficiency	TECH 2.4	η_{PCM}	%	O
		DHW charging cycles per day	TECH 2.5	*DHWcycles*	N° cycles /day	O
		Charge/discharge time	TECH 2.6	tch_{PCM}, $tdis_{PCM}$	h	D/O
UC3 (Montserrat, Spain) & UC4 (UCD Campus, Ireland)	Sorption thermal storage (TCM)	Operating temperature levels	TECH 3.1	Tch_{SOR}, $Tdis_{SOR}$	°C	D/O
		Energy storage capacity	TECH 3.2	ESC_{SOR}	kWh	D/O
		Energy storage efficiency	TECH 3.3	η_{SOR}	%	O
		Charge/discharge power	TECH 3.4	$Qch_{nom,SOR}$, $Qdis_{nom,SOR}$	kW	D/O
		Charge/discharge time	TECH 3.5	tch_{SOR}, $tdis_{SOR}$	h	D/O
All UC	Advanced management algorithms	Optimal cost	TECH 4	$OptCost_{heat}$, $OptCost_{cool}$, $OptCost_{DHW}$	€	O
All UC	Predictive and real-time management tools	Energy peak import/export	TECH 5.1	*EnPeakImp*, *EnPeakExp*	kWh	O
		Computational time of real time management	TECH 5.2	*RTMCompTime*	s	O
		Prediction error	TECH 5.3	*PredictionErr*	%	O

[2] UC = Use Case

[3] D = design parameter, O = operational parameter

All UC	Dynamic & data-driven simulation tool	Total LOLP baseline	TECH 6.1	*TotLOLPbase*	%	O
		Total LOLP future	TECH 6.2	*TotLOLPfut*	%	O
		Total LOLP variation	TECH 6.3	*TotLOLPvar*	%	O
		Internal LOLP baseline	TECH 6.4	*IntLOLPbase*	%	O
		Internal LOLP future	TECH 6.5	*IntLOLPfut*	%	O
		Internal LOLP variation	TECH 6.6	*IntLOLPvar*	%	O

3.2. Energy KPIs

In this section the most relevant KPIs essential to analyse the energy performance of each demonstration sites with respect to primary energy consumption, self-consumption, self-sufficiency, and network efficiency.

Table 6 Energy-related KPI for different use cases.

	Subdomain	KPI	Index	Symbol	UoM	D/O¡Error! Marcador no definido.
Energy domain	Primary energy consumption (PEC)	PEC baseline	EN 1.1	*PECbase*	kWh	O
		PEC future	EN 1.2	*PECfut*	kWh	O
		PEC variation	EN 1.3	*PECvar*	kWh	O
	Self-consumption	Self-consumption baseline	EN 2.1	*SCbase*	%	O
		Self-consumption future	EN 2.2	*SCfut*	%	O
		Self-consumption variation	EN 2.3	*SCvar*	%	O
	Self sufficiency	Self-sufficiency baseline	EN 3.1	*SSbase*	%	O
		Self-sufficiency future	EN 3.2	*SSfut*	%	O
		Self-sufficiency variation	EN 3.3	*SSvar*	%	O
	Energy Flexibility	Lack of ramp probability	EN 4.1	LORP	MW	O
		Insufficient Ramp Resources Expectation	EN 4.2	IRRE	MW	O
		Peak load demand reduction	EN 4.3	$\Delta peakload$	%	O

3.3. Economic KPIs

In this section the most crucial economic indicators which can be used to evaluate the financial feasibility of the HYSTORE technologies are presented.

Table 7 Economic KPIs

	Subdomain	KPI	Index	Symbol	UoM	D/O¡Error! Marcador no definido.
Economic domain	Cost of investment	Cost of investment	ECO 1	*InvCost*	€	O
	Payback period	Payback period	ECO 2	*PBP*	years	O
	Levelised cost of energy	LCOE baseline	ECO 3.1	*LCOEbase*	€/kWh	O
		LCOE future	ECO 3.2	*LCOEfut*	€/kWh	O
		LCOE variation	ECO 3.3	*LCOEvar*	€/kWh	O
	Operating expenses	OPEX baseline	ECO 4.1	*OPEXbase*	€/year	O
		OPEX future	ECO 4.2	*OPEXfut*	€/year	O
		OPEX variation	ECO 4.3	*OPEXvar*	%	O
	Feed-in revenues	Feed-in revenues baseline	ECO 5.1	*FIRbase*	€/year	O
		Feed-in revenues future	ECO 5.2	*FIRfut*	€/year	O

		Feed-in revenues variation	ECO 5.3	*FIRvar*	€/year	O

4. KPIs calculation methods

4.1. Technology KPIs (TECH)

4.1.1. Modular heat pump performance (TECH 1)

4.1.1.1. COP heating (TECH 1.1)

The coefficient of performance (COP) of a heat pump is the ratio between heating or cooling energy provided and work (energy) required, including auxiliary energy consumption for pumping. In the heating configuration, it can be calculated as:

$$COP_{heat}[-] = \frac{Qout_H}{Win_H}$$

where

- $Qout_H$ [kWh] is the heat given to the hot reservoir, i.e. the thermal energy provided to the network in heating mode
- Win_H [kWh] is the electrical energy used by the system in heating mode, including electricity used for auxiliary purposes like pumping

4.1.1.2. COP cooling (TECH 1.2)

In the cooling configuration, the COP is calculated as:

$$COP_{cool}[-] = \frac{Qout_C}{Win_C}$$

where

- $Qout_C$ [kWh] is the heat extracted by the cold reservoir, i.e. the thermal energy removed from the network in cooling mode
- Win_C [kWh] is the electrical energy used by the system in cooling mode, including electricity used for auxiliary purposes like pumping

4.1.1.3. COP DHW with PCM losses (TECH 1.3)

In domestic hot water (DHW) mode, the heat pump provides heat to tap water through an integrated PCM storage. The overall performance of this configuration can be assessed by a specific COP, that includes the storage losses:

$$COP_{DHW}[-] = \frac{Qout_{tapwater}}{Win_{DHW}}$$

where

- $Qout_{tapwater}$ [kWh] is the thermal energy provided to the tap water, measured at the fresh water side of the heat exchanger
- Win_{DHW} [kWh] is the electrical energy used by the system in DHW mode

4.1.1.4. COP DHW without PCM losses (TECH 1.4)

A heat pump COP for DHW mode that doesn't include the losses due the PCM storage can also be defined as:

$$COP_{PCM}[-] = \frac{Qout_{PCM}}{Win_{DHW}}$$

where

- $Qout_{PCM}$ [kWh] is the heat provided to charge the PCM storage, measured at the heating fluid side of the heat exchanger
- Win_{DHW} [kWh] is the electrical energy used by the system

4.1.2. PCM storage performance (TECH 2)

4.1.2.1. Degree of compactness (TECH 2.1)

The degree of compactness of a PCM thermal storage is an indicator of the energy density attainable by the system. It provides an indication of the compactness degree attainable, and information on the required trade-off of PCM storage volume for heat exchange material to achieve certain performance [1]. It is defined as:

$$\phi_{PCM}\ [-] = \frac{V_{PCM}}{V_{TOT}}$$

where

- V_{PCM} [m^3] is the volume of PCM in the storage
- V_{TOT} [m^3] is the total outer volume of the device, calculated considering the geometry of the outermost layer of the unit, excluding the additional volume used for insulation

4.1.2.2. Energy storage capacity (TECH 2.2)

The energy storage capacity for a TES estimates the total amount of heat that the device can store at nominal within a pre-defined temperature range [2] :

$$ESC_{PCM}\ [kWh] = ESCmat_{PCM} + ESCcomp_{PCM}$$

where

- $ESCmat_{PCM}$ [kWh] is the energy storage capacity of the phase change material, including latent and sensible heat within a pre-defined temperature range around the phase transition temperature
- $ESCcomp_{PCM}$ [kWh] is the sensible heat that can be stored in all non-PCM parts of the storage within a pre-defined temperature range around the phase transition temperature

4.1.2.3. Energy storage density (TECH 2.3)

The energy storage density is a parameter that measures the ratio between the amount of heat that a system can store and the space it occupies. It is calculated as :

$$ESD_{PCM}\left[\frac{kWh}{m^3}\right] = \frac{ESC_{PCM}}{V_{TOT}}$$

where

- ESC_{PCM} [kWh] is the total energy storage capacity of the PCM
- V_{TOT} [m^3] is the total outer volume of the PCM system, calculated considering the geometry of the outermost layer of the unit, excluding the additional volume used for insulation

Further details about the calculation of ESC_{PCM} and ESD_{PCM} can be found in the final report of the IEA-ECES Annex 30 [3].

4.1.2.4. Energy storage efficiency (TECH 2.4)

The PCM energy storage efficiency is calculated as the energy recovered from the storage during discharging over the energy supplied during charging and the one supplied intentionally to components. When calculating this indicator, the temperature levels of heat source and load have to be specified, as well as the stand-by period [4].

$$\eta_{PCM}[\%] = \frac{Qdis_{PCM}(\overline{Tdis_{PCM}})}{Qch_{PCM}(\overline{Tch_{PCM}}) + Qaux_{PCM}}$$

where

- $Qdis_{PCM}$ [kWh] is the energy recovered from storage at an average discharge temperature $\overline{Tdis}_{PCM}$
- Qch_{PCM} [kWh] is the energy supplied to the storage at an average charge temperature $\overline{Tch}_{PCM}$
- $Qaux_{PCM}$ [kWh] is the energy supplied to auxiliary components

4.1.2.5. DHW charging cycles per day (TECH 2.5)

The number of charging cycles required in cooling mode to satisfy the DWH demand in one day can be calculated as:

$$DHWcycles\left[\frac{N°\ cycles}{day}\right] = \frac{Qout_{DWH\_daily}}{ESC_{PCM} - Eloss\_cycle_{PCM}}$$

where

- $Qout_{DWH\_daily}$ [kWh/day] is the daily thermal energy requirement for DWH
- ESC_{PCM} [kWh] is the energy storage capacity of the PCM storage, hence the energy available for each charging cycle
- $Eloss\_cycle_{PCM}$ [kWh] is the energy lost by the PCM storage in each complete cycle

4.1.2.6. Charge/discharge time (TECH 2.6)

The charge and discharge times are design parameters indicating the time needed to complete the charge or discharge process. Neglecting any storage or standby process, they are defined as :

$$tch_{PCM}\ [h] = \frac{ESC_{PCM}}{\dot{Q}ch_{nom,PCM}(\overline{Tch}_{PCM})}$$

$$tdis_{PCM}\ [h] = \frac{ESC_{PCM}}{\dot{Q}dis_{nom,PCM}(\overline{Tdis}_{PCM})}$$

where

- ESC_{PCM} [kWh] is the energy storage capacity of the PCM
- $\dot{Q}ch_{nom,PCM}$ [kW] is the nominal charge power at an average charge temperature $\overline{Tch}_{PCM}$
- $\dot{Q}dis_{nom,PCM}$ [kW] is the nominal discharge power at an average discharge temperature $\overline{Tdis}_{PCM}$

4.1.3. Sorption storage performance (TECH 3)

4.1.3.1. Operating temperature levels (TECH 3.1)

The actual operating temperatures relative to sorption storage are indicated with Tch_{SOR} [°C] and $Tdis_{SOR}$ [°C] and can be directly measured during the testing phase.

4.1.3.2. Energy storage capacity (TECH 3.2)

The energy storage capacity of the sorption storage is the total amount of heat that can be stored by the system. Heat is mainly stored in the TES material, but also in the components that are in contact with the material [4]. This can be relevant or not according to the storage time between charge and discharge [5]. The total capacity can be calculated as :

$$ESC_{SOR}\ [kWh] = ESCmat_{SOR} + ESCcomp_{PCM}$$

where

- $ESCmat_{PCM}$ [kWh] is the energy storage capacity of the phase change material
- $ESCcomp_{PCM}$ [kWh] is the sensible heat that can be stored in the components that are in contact with the material

Further details about the definition and calculation of ESC_{SO} can be found in the final report of the IEA-ECES Annex 30 [3].

4.1.3.3. Energy storage efficiency (TECH 3.3)

The sorption energy storage efficiency is calculated as the energy recovered from the storage during discharging over the energy supplied during charging and the one supplied intentionally to components. When calculating this indicator, the temperature levels of heat source and load have to be specified, as well as the stand-by period [4].

$$\eta_{SOR}[\%] = \frac{Qdis_{SOR}}{Qch_{SOR} + Qaux_{SOR}}$$

where

- $Qdis_{SOR}$ [kWh] is the energy recovered from storage
- Qch_{SOR} [kWh] is the energy supplied to the storage
- $Qaux_{SOR}$ [kWh] is the energy supplied to auxiliary components

4.1.3.4. Charge/discharge power (TECH 3.4)

The nominal discharge power $\dot{Q}dis_{nom,SOR}$ [kW] and nominal charge power $\dot{Q}ch_{nom,SOR}$ [kW] are the thermal power supplied and stored by the storage device respectively during discharge and charge [4]. They can be directly measured on the system during the operative phase.

4.1.3.5. Charge/discharge time (TECH 3.5)

The charge and discharge times are design parameters indicating the time needed to complete the charge or discharge process. Neglecting any storage or standby process, they are defined as :

$$tch_{SOR}\ [h] = \frac{ESC_{SOR}}{\dot{Q}ch_{nom,SOR}}$$

$$tdis_{SOR}\ [h] = \frac{ESC_{SOR}}{\dot{Q}dis_{nom,SOR}}$$

where

- ESC_{SOR} [kWh] is the energy storage capacity
- $\dot{Q}ch_{nom,SOR}$ [kW] is the nominal charge power
- $\dot{Q}dis_{nom,SOR}$ [kW] is the nominal discharge power

4.1.4. Management algorithms performance (TECH 4)

4.1.4.1. Optimal cost (TECH 4.1)

The equation below shows the cost function which can be optimised based on different heat pump control mode. The first term ensures the PV power self-consumption if it is allowed by the system constraints, the second term decreases the grid electricity cost, while the third term increases feed-to-the-grid electricity.

In case of heating:

$$OptCost_{heat}[€] = \sum_{i=1}^{n} \alpha.\left(\frac{Qout_H}{COP_{heat}} - P_{pv}\right)^2 + \beta.EP_{i,in}.P_{g,in} - \gamma.\frac{P_{g,out}}{EP_{i,out}}$$

In case of cooling:

$$OptCost_{cool}[€] = \sum_{i=1}^{n} \alpha.\left(\frac{Qout_C}{COP_{cool}} - P_{pv}\right)^2 + \beta.EP_{i,in}.P_{g,in} - \gamma.\frac{P_{g,out}}{EP_{i,out}}$$

In case of DHW:

$$OptCost_{DHW}[€] = \sum_{i=1}^{n} \alpha.\left(\frac{Qout_{DHW}}{COP_{DHW}} - P_{pv}\right)^2 + \beta.EP_{i,in}.P_{g,in} - \gamma.\frac{P_{g,out}}{EP_{i,out}}$$

where:

- $EP_{i,in}$ [€/kWh] the price of electricity imported from the grid at time unit i
- $EP_{i,out}$ [€/kWh] the price of electricity exported to the grid at time unit i
- $Qout_H$, $Qout_C$, and $Qout_{DHW}$ [kWh] are the required energy supply for heating, cooling and DHW respectively
- COP_{heat}, COP_{cool}, and COP_{DHW} are the calculated coefficient of performance for heating, cooling and DHW respectively
- P_{pv} [kWh] the produced photovoltaic energy
- $P_{g,in}$ and $P_{g,out}$ [kWh] are respectively the electricity energy imported from the grid (positive values) and the one exported to (negative values)
- n is the control horizon
- α, β, and γ are the weighting coefficients

4.1.5. Predictive and real-time management tools performance (TECH 5)

4.1.5.1. Energy peak import/export (TECH 5.1)

Energy peak import/export refers to the maximum value of the aggregate electricity import/export of the community over a defined timeframe (day, week, month, year). In equation form, it can be expressed as:

$$EnPeakImp\ [kWh] = \max(GEin(t))$$

$$EnPeakExp\ [kWh] = \max(GEout(t))$$

where

- $GEin(t)$ [kWh] is the timeserie of the energy taken from the external grid during each timestep Δt
- $GEout(t)$ [kWh] is the timeserie of the energy fed to the the external grid during each timestep Δt
- Δt [min] is the simulation timestep (15 min or 60 min)

4.1.5.2. Computational time of real time management (TECH 5.2)

The computational time required by the control tools performing real time management can be calculated in the tool itself and indicated as $RTMCompTime$ [s].

4.1.5.3. Prediction error (TECH 5.3)

In order to optimize the system operations, the ICT tool uses predictions. The accuracy of the prediction for a single parameter x can be assessed through the prediction error, calculated as:

$$PredictionErr\ [\%] = \left|\frac{x_{prediction} - x_{real}}{x_{prediction}}\right| \cdot 100$$

where for the parameter in object

- x_{real} is the real value
- $x_{prediction}$ is the predicted value

4.1.6. Dynamic and data-driven simulation tools (TECH 6)

4.1.6.1. Total loss of load probability baseline (TECH 6.1)

The Loss of Load Expectation (LOLE) and Loss of Load Probability (LOLP) indices are generally used to measure a generation system reliability and ability to meet the load demand. LOLE denotes the expected average time (usually days or hours in a number of years) during which the system is being on outages, *i.e.* when the load exceeds the available generation capacity. LOLP instead describes the probability of outages during a given period.

This parameter can be calculated through a Monte Carlo simulation, varying different parameters (such as weather conditions or control strategies), and expressed in the baseline scenario as:

$$TotLOLPbase_{el}\ [\%] = \mathrm{p}(Outage_{el})_{base}$$

$$TotLOLPbase_{th}\ [\%] = \mathrm{p}(Outage_{th})_{base}$$

where $\mathrm{p}(\,)_{base}$ indicates the probability that the $Outage$ event occurs in a number N of years in the baseline case, calculated through a Monte Carlo simulation.

4.1.6.2. Total loss of load probability future (TECH 6.2)

In a future scenario, the total LOLP can be calculated in the same way:

$$TotLOLPfut_{el}\ [\%] = \mathrm{p}(Outage_{el})_{fut}$$

$$TotLOLPfut_{th}\ [\%] = \mathrm{p}(Outage_{th})_{fut}$$

where $\mathrm{p}(\,)_{fut}$ indicates the probability that the $Outage$ event occurs in a number N of years in a future case, calculated through a Monte Carlo simulation.

4.1.6.3. Total loss of load probability variation (TECH 6.3)

The total LOLP variation with respect to the baseline, in percentage, can be defined as:

$$TotLOLPvar_{el}\ [\%] = \frac{TotLOLPfut_{el} - TotLOLPbase_{el}}{TotLOLPbase_{el}} \cdot 100$$

$$TotLOLPvar_{th}\ [\%] = \frac{TotLOLPfut_{th} - TotLOLPbase_{th}}{TotLOLPbase_{th}} \cdot 100$$

4.1.6.4. Internal loss of load probability baseline (TECH 6.4)

For a system that relies both on internal energy production and external grid supply, an internal LOLP can be calculated from simulation. Assuming that baseline power profiles are available in discrete form with a timestep resolution of Δt, the indicators can be expressed as:

$$IntLOLEbase_{el}\left[\frac{hours}{N\ years}\right] = \sum_{t=0}^{N\ years} Outage_{t,el,base} \cdot \Delta t \qquad IntLOLPbase_{el}\ [\%] = \frac{IntLOLEbase_{el}}{N \cdot 8760}$$

$$IntLOLEbase_{th}\left[\frac{hours}{N\ years}\right] = \sum_{t=0}^{N\ years} Outage_{t,th,base} \cdot \Delta t \qquad IntLOLPbase_{th}\ [\%] = \frac{IntLOLEbase_{th}}{N \cdot 8760}$$

where

- $Outage_{t,base}$ [-] is a binary variable representing the occurrence of an outage at any timestep in the baseline scenario, according to the definition:

$$Outage_{t,base} = \begin{cases} 1\ if\ UP_t > IP_{t,base} \\ 0\ if\ UP_t \le IP_{t,base} \end{cases}$$

  where

  - UP_t [W] is the used power at timestep t
  - $IP_{t,base}$ [W] is the internally produced power at timestep t in the baseline scenario
- Δt [s, h] is the timestep duration
- N [-] is the number of years considered
- 8760 [h] are the hours in one year

4.1.6.5. Internal loss of load probability future (TECH 6.5)

In a future scenario, the internal LOLP can be calculated in the same way:

$$IntLOLEfut_{el}\left[\frac{hours}{N\ years}\right] = \sum_{t=0}^{N\ years} Outage_{t,el,fut} \cdot \Delta t \qquad IntLOLPfut_{el}\ [\%] = \frac{IntLOLEfut_{el}}{N \cdot 8760}$$

$$IntLOLEfut_{th}\left[\frac{hours}{N\ years}\right] = \sum_{t=0}^{N\ years} Outage_{t,th,fut} \cdot \Delta t \qquad IntLOLPfut_{th}\ [\%] = \frac{IntLOLEfut_{th}}{N \cdot 8760}$$

where

- $Outage_t$ [-] is a binary variable representing the occurrence of an outage at any timestep in a future scenario, according to the definition:

$$Outage_{t,fut} = \begin{cases} 1\ if\ UP_t > IP_{t,fut} \\ 0\ if\ UP_t \le IP_{t,fut} \end{cases}$$

  where

  - UP_t [W] is the used power at timestep t
  - $IP_{t,fut}$ [W] is the internally produced power at timestep t in a future scenario
- Δt [s, h] is the timestep duration

- N [-] is the number of years considered
- 8760 [h] are the hours in one year

4.1.6.6. Internal loss of load probability variation (TECH 8.6)

The internal LOLP variation with respect to the baseline, in percentage, can be defined as:

$$IntLOLPvar_{el}\ [\%] = \frac{IntLOLPfut_{el} - IntLOLPbase_{el}}{IntLOLPbase_{el}} \cdot 100$$

$$IntLOLPvar_{th}\ [\%] = \frac{IntLOLPfut_{th} - IntLOLPbase_{th}}{IntLOLPbase_{th}} \cdot 100$$

4.2. Energy KPIs (EN)

4.2.1. Primary energy consumption (EN 1)

4.2.1.1. Primary energy consumption baseline (EN 1.1)

The baseline primary energy consumption $PECbase$ [kWh] corresponds to the total primary energy consumed by the system before the installation and implementation of new technologies or tools. It includes the total energy imported from the grid and produced locally, multiplied by the country-specific Primary Energy Factor (PEF).

4.2.1.2. Primary energy consumption future (EN 1.2)

The future primary energy consumption $PECfut$ [kWh] corresponds to the total primary energy consumed by the system after the installation and implementation of new technologies or tools.

4.2.1.3. Primary energy consumption variation (EN 1.3)

The variation in primary energy consumption can be calculated as:

$$PECvar\ [kWh] = PECbase - PECfut$$

4.2.2. Self-consumption (EN 2)

4.2.2.1. Self-consumption baseline (EN 2.1)

Self-consumption refers to the percentage of energy produced by internal sources that is consumed by the local community, as opposed to be sold to the external grid. It can be calculated as:

$$SCbase_{el}[\%] = \frac{UE_{el,int,base}}{IE_{el,base}} \cdot 100$$

$$SCbase_{th}[\%] = \frac{UE_{th,int,base}}{IE_{th,base}} \cdot 100$$

where

- $UE_{int,base}$ [kWh] is the energy consumed in the system coming from internal production in the baseline scenario

- IE_{base} [kWh] is the total energy produced locally in the community in the baseline scenario

4.2.2.2. Self-consumption future (EN 2.2)

As in the baseline case, self-consumption in a future scenario can be calculated as:

$$SCfut_{el}[\%] = \frac{UE_{el,int,fut}}{IE_{el,fu}} \cdot 100$$

$$SCfut_{th}[\%] = \frac{UE_{th,int,fut}}{IE_{th,fut}} \cdot 100$$

where

- $UE_{int,fut}$ [kWh] is the energy consumed in the system coming from internal production in a future scenario
- IE_{fut} [kWh] is the total energy produced locally in the community in a future scenario

4.2.2.3. Self-consumption variation (EN 2.3)

The self-consumption variation between the baseline and future scenario, in percentage, can be expressed as:

$$SCvar_{el}\,[\%] = \frac{SCfut_{el} - SCbase_{el}}{SCbase_{el}} \cdot 100$$

$$SCvar_{th}\,[\%] = \frac{SCfut_{th} - SCbase_{th}}{SCbase_{th}} \cdot 100$$

4.2.3. Self-sufficiency (EN 3)

4.2.3.1. Self-sufficiency baseline (EN 3.1)

Self-sufficiency refers to the percentage of total energy consumed by the local community that is supplied by the local production, as opposed to be supplied by the external grid. It can be calculated as:

$$SSbase_{el}[\%] = \frac{UE_{el,int,base}}{UE_{el,base}} \cdot 100$$

$$SSbase_{th}[\%] = \frac{UE_{th,int,base}}{UE_{th,base}} \cdot 100$$

where

- $UE_{int,base}$ [kWh] is the energy consumed in the system coming from internal production in the baseline scenario
- UE_{base}[kWh] is the total energy demanded by the local community in the baseline scenario

4.2.3.2. Self-sufficiency future (EN 3.2)

As in the baseline case, self-sufficiency in a future scenario can be calculated as:

$$SSfut_{el}[\%] = \frac{UE_{el,int,fut}}{UE_{el,fut}} \cdot 100$$

$$SSfut_{th}[\%] = \frac{UE_{th,int,fut}}{UE_{th,fut}} \cdot 100$$

where

- $UE_{int,fut}$ [kWh] is the energy consumed in the system coming from internal production in a future scenario
- UE_{fut} [kWh] is the total energy demanded by the local community in a future scenario

4.2.3.3. Self-sufficiency variation (EN 3.3)

The self-sufficiency variation between the baseline and future scenario, in percentage, can be expressed as:

$$SSvar_{el}\ [\%] = \frac{SSfut_{el}\ - SSbase_{el}}{SCbase_{el}} \cdot 100$$

$$SSvar_{th}\ [\%] = \frac{SSfut_{th}\ - SSbase_{th}}{SSbase_{th}} \cdot 100$$

4.2.4. Energy flexibility (EN 4)

4.2.4.1. Lack of Ramp Probability (LORP) (EN 4.1)

The Lack of ramp probability (LORP) should be calculated in various ways, considering the time scale of the assessment. Thatte and Xie [13] propose different types of LORP. The system-wide LORPs provides an assessment of the adequacy of the available system ramping capability from dispatched generators to meet both expected changes and uncertainty in forecasted net load. It is defined for the ramp up and the ramp down cases as can be seen from the equations below: [14]

$$LORP_s^{up,\tau}(t) = \mathbb{P}\,(\sum_{i\in 1}\left\{P_i^g(t) + \min\left(\tau R_i, P_i^{max} - P_i\ \ (t)\right)\right\} < \widetilde{P_s^l}(t+\tau))$$

$$LORP_s^{dn,\tau}(t) = \mathbb{P}\,(\sum_{i\in 1}\{P_i^g(t) - \min(\tau R_i, P_i\ \ (t) - P_i^{max}\ -)\} > \widetilde{P_s^l}(t+\tau))$$

Also, the zonal LORP$_z$, should be defined in which inter-zonal flows are considered.

$$LORP_s^{up}(t) = \mathbb{P}\,(\sum_{i\in 1^z}\left(P_i^g(t) + RC_z(y) < \widetilde{P_z^l}(t+\tau)\right)$$

The zonal LORP for down ramp can be similarly defined [13].

Where

- $P_i^g(t)$ is dispatch output of generator i at time t

- R_i is One interval (5 min) ramp rate of generator i (MW)
- P_i^{max} is maximum output of generator i (MW)
- $P_i\ (t)$ is Output of generator i at time t (MW)
- $\widetilde{P_s^l}(t+\tau)$is system-wide net load for the interval τ time steps in the future. It is assumed to be a Gaussian random variable with known mean and standard deviation. $RC_z(t)$ is ramp capability (5min) for zone z at time t (MW)
- $\widetilde{P_z^l}(t+\tau)$ is net load of zone z for the interval τ time steps
- I(I_z) Set of generators (set of generators in zone z)

4.2.4.2. Insufficient Ramp Resources Expectation (IRRE) (EN 4.2)

IRRE is the expected number of times for a given period that a system will not be capable to meet changes in net load. It can be calculated as the cumulative probability that the flexibility will not be sufficient to overcome the ramps. It offers a high level insight into the flexibility of a system [14]. This indicator can be calculated by following algorithm proposed by Eamonn et al. [15].

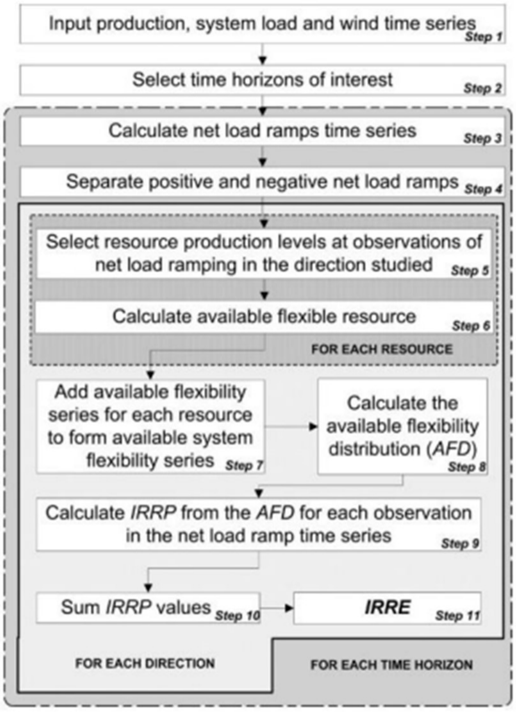

Figure 11 Algorithm computing the **IRRE, adopted from Eamonn et al. [15].**

After calculating the net load ramps ($NLR_{t,i,\pm}$) for each observation t, and the available flexibility distribution for time interval *i* in both direction ($AFD_{i,\pm}$), it should be possible to calculate for each observation *t*, for each horizon, *i*, the insufficient ramping resource probability ($IRRP_{t,i,\pm}$):

$$IRRP_{t,i,\pm} = AFD_{i,\pm}(NLR_{i,\pm} - 1)$$

And finally, the insufficient ramping resource expectation in each direction for a time interval *i*:

$$IRRE_{i,\pm} = \sum_{t \in T_\pm} IRRP_{t,i,\pm}$$

4.2.4.3. Peak load demand reduction (EN 4.3)

The main utilisation of this indicator is to evaluate improved ancillary services for network operation, storage integration, demand response, and active demand response [16]. This indicator measures the maximum percentage decrease of peak load demand in an area by a flexibility provider resource [16].

$$\Delta_{PeakLoad} = \frac{PeakLoad_{Base} - PeakLoad_{Fut}}{PeakLoad_{Base}} \ [\%]$$

Where

- $PeakLoad_{Base}$ is the peak load of the base scenario (MW),
- $PeakLoad_{Fut}$ is the peak load of the scenario after implementation of the HYSTORE TES solutions (MW),

4.3. Economic KPIs (ECO)

4.3.1. Cost of investment (ECO 1)

The cost of investment parameter refers to the total estimated amount to be spent for the integration and installation of new technologies and tools, as simulated in the project. It can be calculated as:

$$InvCost\ [€] = \sum_{y=0}^{L} \frac{Inv_{y,base}}{(1+r)^y}$$

where:

- $Inv_{y,base}$ [€/year] is the yearly estimated investment amount for improvements
- $(1+r)^y$ [-] is the compound interest factor, where r is the annual discount rate

4.3.2. Payback period (ECO 2)

The payback period refers to the amount of time it takes to recover the cost of an investment. It is calculated by comparing the cost of the initial investment with the annual cash flow:

$$PBP\ [years] = \frac{Inv_0}{\sum_{y=0}^{L} \frac{Fuel_y + Elect_y + Op\&Main_y - Rev_y - Sav_y}{(1+r)^y}}$$

where

- Inv_0 [€] is the total initial investment cost at year 0
- $Fuel_y$ [€] is the yearly fuel cost

- $Elect_y$ [€] is the yearly electricity cost
- $Op\&Main_y$ [€] is the yearly operation & maintenance cost
- Rev_y [€] are the yearly revenues coming from energy selling
- Sav_y [€] are the yearly savings due to the new system or configuration
- $(1+r)^y$ [-] is the compound interest factor, where r is the annual discount rate
- L [years] is the estimated lifetime of the project

4.3.3. Levelized cost of energy (ECO 3)

4.3.3.1. Levelized cost of energy baseline (ECO 3.1)

The levelized cost of energy (LCOE) is a measure of the lifecycle cost divided by the lifetime energy production and use of an energy system. In the network in object, we can distinguish the levelized cost of electricity ($LCOE_{el}$) and levelized cost of heat ($LCOE_{th}$), respectively defined as:

$$LCOEbase_{el}\left[\frac{€}{kWh}\right]=\frac{\sum_{y=0}^{L}\frac{Inv_{el,y,base}+Fuel_{el,y,base}+Op\&Main_{el,y,base}}{(1+r)^y}}{\sum_{y=0}^{L}\frac{FE_{el,y,base}+IE_{el,y,base}}{(1+r)^y}}$$

$$LCOEbase_{th}\left[\frac{€}{kWh}\right]=\frac{\sum_{y=0}^{L}\frac{Inv_{th,y,base}+Fuel_{th,y,base}+Op\&Main_{th,y,base}}{(1+r)^y}}{\sum_{y=0}^{L}\frac{FE_{th,y,base}+IE_{th,y,base}}{(1+r)^y}}$$

where:

- $Inv_{y,base}$ [€] is the yearly investment cost in the baseline scenario
- $Fuel_{y,base}$ [€] is the yearly fuel cost in the baseline scenario
- $Op\&Main_{y,base}$ [€] is the yearly operation & maintenance cost in the baseline scenario
- $FE_{y,base}+IE_{y,base}$ [kWh] is the sum of final and internally produced energy in the system in the baseline scenario
- $(1+r)^y$ [-] is the compound interest factor, where r is the annual discount rate
- L [years] is the estimated lifetime of the project

4.3.3.2. Levelized cost of energy future (ECO 3.2)

As in the baseline case, LCOE in a future scenario can be calculated as:

$$LCOEfut_{el}\left[\frac{€}{kWh}\right]=\frac{\sum_{y=0}^{L}\frac{Inv_{el,y,fut}+Fuel_{el,y,fut}+Op\&Main_{el,y,fut}}{(1+r)^y}}{\sum_{y=0}^{L}\frac{FE_{el,y,fut}+IE_{el,y,fut}}{(1+r)^y}}$$

$$LCOEfut_{th}\left[\frac{€}{kWh}\right]=\frac{\sum_{y=0}^{L}\frac{Inv_{th,y,fut}+Fuel_{th,y,fut}+Op\&Main_{th,y,fut}}{(1+r)^y}}{\sum_{y=0}^{L}\frac{FE_{th,y,fut}+IE_{th,y,fut}}{(1+r)^y}}$$

where:

- $Inv_{y,fut}$ [€] is the yearly investment cost in a future scenario
- $Fuel_{y,fut}$ [€] is the yearly fuel cost in a future scenario
- $Op\&Main_{y,fut}$ [€] is the yearly operation & maintenance cost in a future scenario
- $FE_{y,fut} + IE_{y,fut}$ [kWh] is the sum of final and internally produced energy in the system in a future scenario
- $(1+r)^y$ [-] is the compound interest factor, where r is the annual discount rate
- L [years] is the estimated lifetime of the project

4.3.3.3. Levelized cost of energy variation (ECO 3.3)

The LCOE variation between the baseline and future scenario, can be expressed as:

$$LCOEvar_{el}\left[\frac{€}{kWh}\right] = LCOEbase_{el} - LCOEfut_{el}$$

$$LCOEvar_{th}\left[\frac{€}{kWh}\right] = LCOEbase_{th} - LCOEfut_{th}$$

4.3.4. Operational expenses (ECO 4)

4.3.4.1. OPEX baseline (ECO 4.1)

The operation expenses (OPEX) parameter represents the cash expenditure that occurs every year and can be expressed in monetary unit per year. In the baseline case it can be calculated as :

$$OPEXbase\left[\frac{€}{year}\right] = Fuel_{y,base} + Elect_{y,base} + Op\&Main_{y,base}$$

where:

- $Fuel_y$ [€/year] is the yearly fuel cost in the baseline scenario
- $Elect_y$ [€/year] is the yearly cost of imported electricity in the baseline scenario
- $Op\&Main_y$ [€/year] is the yearly operation & maintenance cost in the baseline scenario

4.3.4.2. OPEX future (ECO 4.2)

As in the baseline case, the OPEX in a future scenario can be calculated as:

$$OPEXfut\left[\frac{€}{year}\right] = Fuel_{y,fut} + Elect_{y,fut} + Op\&Main_{y,fut}$$

where:

- $Fuel_y$ [€/year] is the yearly fuel cost in a future scenario
- $Elect_y$ [€/year] is the yearly cost of imported electricity in a future scenario
- $Op\&Main_y$ [€/year] is the yearly operation & maintenance cost in a future scenario

4.3.4.3. OPEX variation (ECO 4.3)

The OPEX variation between the baseline and future scenario, in percentage, can be expressed as:

$$OPEXvar\ [\%] = \frac{OPEXbase - OPEXfut}{OPEXbase}$$

4.3.5. Feed-in revenues (ECO 5)

4.3.5.1. Feed-in revenues baseline (ECO 5.1)

An energy system with internal production can generate revenues by selling electrical energy to the external grid at a predefined feed-in tariff. The total yearly feed-in revenues (FIR) in the baseline scenario can be indicated as:

$$FIRbase\left[\frac{€}{year}\right] = GEout_{yearly,base} \cdot FeedInTariff$$

where

- $GEout_{yearly,base}$ [kWh/year] is the yearly amount of energy sold to the external grid in the baseline scenario
- $FeedInTariff$ [€/kWh] is the tariff per kWh that the grid owner pays to receive that energy. The amount and time dependency of the feed in tariff highly depends on country regulations.

4.3.5.2. Feed-in revenues future (ECO 5.2)

After the implementation of the new technologies and tools, the future feed in revenues are:

$$FIRfut\left[\frac{€}{year}\right] = GEout_{yearly,fut} \cdot FeedInTariff$$

where

- $GEout_{yearly,fut}$ [kWh/year] is the yearly amount of energy sold to the external grid in a future scenario
- $FeedInTariff$ [€/kWh] is the tariff per kWh that the grid owner pays to receive that energy. The amount and time dependency of the feed in tariff highly depends on country regulations.

4.3.5.3. Feed-in revenues variation (ECO 5.3)

An energy system with internal production can generate revenues by selling electrical energy to the external grid at a predefined feed-in tariff. The total yearly revenues can be indicated as:

$$FIRvar\left[\frac{€}{year}\right] = FIRfut - FIRbase$$

5. Conclusions

The HYSTORE project will develop and validate an innovative set of TES concepts, based on the combination of cutting-edge technology components, namely, ALL-IN-ONE PCM solution, LOW-TEMP PCM HEATING&COOLING solution, PCM HEATING solution and TCM HEATING&COOLING solution. The four novel TES solutions will be utilised for heating/cooling. Moreover, the HYSTORE project intends to promote the use of thermal energy storage as an enabler to enhance the flexible and reliable operation of buildings with both power and thermal systems as decentralised energy resources, exploiting the increasing share of renewables and facilitating the implantation of demand side management strategies. The HYSTORE project is aiming at increasing the system efficiency by 20% and decreasing the CAPX and OPEX 50% and 10%, respectively. The purpose of the HYSTORE D 1.2 - KPI analysis of technologies and pilots' operations, is to develop a methodology for the evaluation of the HYSTORE solutions and the use cases through a quantitative measurement of the performances during the operation phase. Key performance indicators (KPIs) are essential metrics utilised for analysing and optimising the operation in any project. Therefore, accurate definition of such KPIs can facilitate performance evaluation of the overall project and to assure that all utilised technologies are performing efficiently. The HYSTORE KPIs are proposed according to the technologies that are used in the project and based on the needs of the stakeholders involved. These KPIs will be used to evaluate the HYSTORE solution in four different demonstration sites. The suggested KPIs are categorised in three different categories which are listed below, and in Figure 12 KPIs diagram.

1. **Technology KPIs**, aimed at evaluating the hardware and software technologies that will be used at the HYSTORE demonstration sites, including the thermal energy storage systems.
2. **Energy KPIs,** aimed at assessing the energy efficiency of the demo sites and technology package during the operation;
3. **Economic indicators**, providing the evaluation of the economic impact for the involved stakeholders and main end-users;

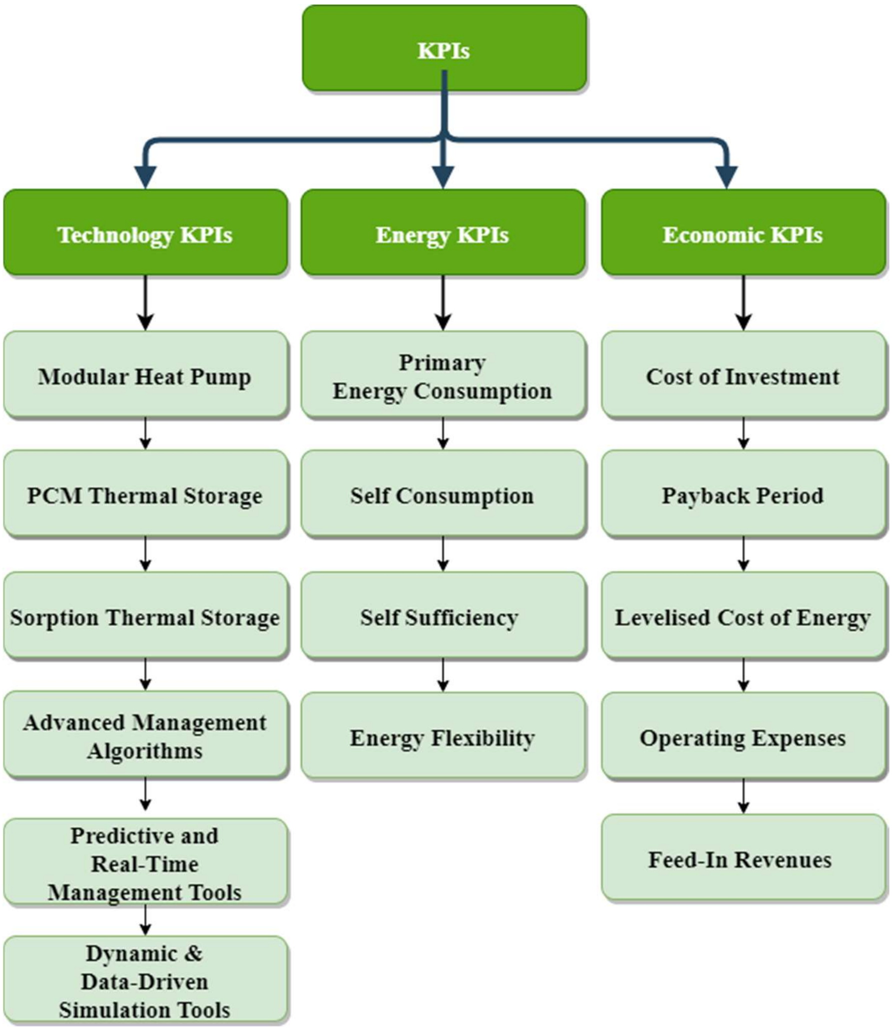

Figure 12 KPIs diagram

6. Nomenclature

CAPEX	Capital Expenses
C	Cooling
CHP	Combined Heat and Power
COP	Coefficient of Performance
D	Design (parameter)
DH	District Heating
DHC	District Heating and Cooling
DHW	Domestic Hot Water
ESC	Energy Storage Capacity
ESD	Energy Storage Density
FIR	Feed-in Revenue
GHG	Greenhouse Gas
H	Heating
KET	Key Enabling Technology
KPI	Key Performance Indicator
LCOE	Levelized Cost of Energy
LHV	Lower Heating Value
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
O	Operational (parameter)
OPEX	Operational Expenses
PBP	Payback Period
PCM	Phase Change Material
PEC	Primary Energy Consumption
PEF	Primary Energy Factor
PV	Photovoltaic
Q	Thermal Energy Output
RES	Renewable Energy Source
RTM	Real Time Management
SC	Self-consumption
SOR	Sorption Storage
SS	Self-sufficiency
TCM	Thermochemical
TES	Thermal Energy Storage
UC	Use Case
UoM	Unit of Measure
W	Electricity Input

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