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Innovative compact HYbrid electrical/thermal storage systems for low energy BUILDings

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HYBUILD

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Publishable executive summary

HYBUILD is an EU Horizon 2020 - funded project, led by COMSA Corporación, which will develop two innovative compact hybrid electrical/thermal storage systems for stand-alone and district connected buildings.

Deliverable 1.3 "Requirements: Key Performance Indicators, system components and performance targets" reports the outcomes of Task 1.5 "Key Performance Indicators". The objective of this task is to define a number of significant performance indicators (namely the Key Performance Indicators, KPIs) to be used at different stages of the project to provide means for the measurement and management of the progress towards project goals and evaluate the impact of the HYBUILD solutions, as a function of different cases of application. The performance indicators should allow evaluation and comparison and to do this they should have some characteristics described below. They should be:

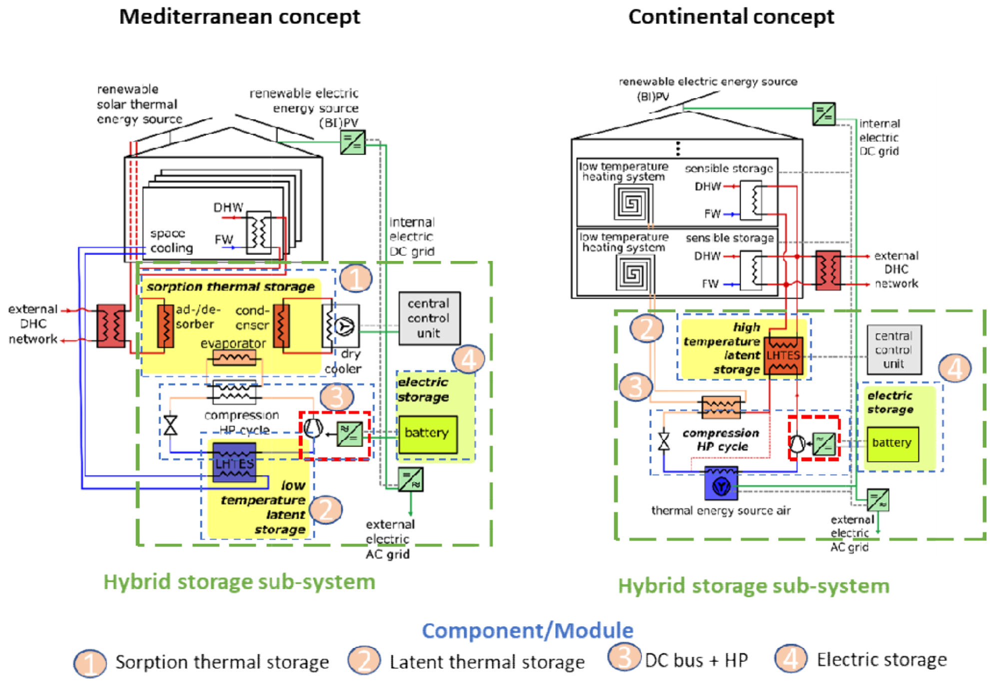
- Unique, that means a single and clear definition.
- Measurable, ideally quantitative, or else measurable with clear, concise measurement attributes.
- Applicable not only to specific cases, sizes and processes, but have a wide range of applications.
- Relevant: it should be meaningful enough to the purposes of the system and specific to the characteristics of its processes and components.

The present report describes the process followed to define the performance indicators, and to select the most significant ones.

Work Methodology

First, a list of over 40 performance indicators has been compiled with the cooperation of consortium partners. The PIs shall be compliant with the target expressed in the DoA and in the proposal call and take into account the specific features of the HYBUILD technologies. In particular, the HYBUILD concepts are articulated according to a hierarchical structure consisting of three different levels, namely

- **Core components/modules** (L1), referring to the individual sorption thermal storage, high density latent thermal storage, DC controller and electrical storage adopted to implement the HYBUILD concepts.
- **Hybrid storage sub-systems** (L2), referring to the combination of multiple L1 core components/modules.
- **Overall building system** (L3), referring to the L2 sub-systems installed into the building, considering also the renewable solar generation (from photovoltaic and/or solar collectors), the sensible water storage (for the continental climate) and the building energy management system. Therefore, performance indicators are classified according to the hierarchical level to which they apply.



Indicators referred to L3 have been additionally subcategorised into

- Energy related PIs;
- Environmental related PIs;
- Comfort related PIs;
- Economic related PIs;
- Installation related PIs.

For each of the identified PIs, the following information have been reported

- Indicator name;
- Definition, with some explanation about how the PI is calculated;
- Unit of measurement;
- Application level (i.e. building, sub-system or component/module).

Finally, seven key performance indicators have been picked from the list, as the most significant ones to assess HYBUILD systems performance, in accordance with the overall project objectives. The selected Key performance indicators are reported in the table below, together with the system level to which they apply.

	Key Performance Indicators	Application level
KPI.1	Thermal Energy Storage Density	**L1**
KPI.2	Seasonal Energy Performance	**L2 – L3**
KPI.3	Share of renewable and self-consumption	**L2 – L3**
KPI.4	Energy savings and CO_2 emission savings	**L1 - L2 - L3**
KPI.5	Compactness	**L3**
KPI.6	Flexibility	**L2 – L3**
KPI.7	Return on Investment	**L3**

The KPIs will be quantified during the project and used on one side to verify each systems performance during the development stage, by means of dynamic simulations results (WP4), and on the other side to evaluate the performance of the systems installed at demo sites, based on the monitored parameters (WP6) and possibly comparing this data with the pre-renovation ones.

Acronyms and Abbreviations

KPI	Key Performance Indicators
PV	Photovoltaic
HP	Heat Pump
BESS	Battery energy storage system
PI	Performance Indicators
NBK	Nobatek
UCY	University of Cipro
EURAC	Eurac Research
UDL	University of Lleida
ENG	Engineering
NTUA	University of Athens
TES	Thermal Energy Storage
WP	Work package
DC	Direct current
AC	Alternative Current
GHG	Green House Gases
ROI	Return of Investment
NPV	Net present value
SEER	Seasonal Energy ratio
SCOP	Seasonal Coefficient of performance
DHC	District heating and cooling
DR	Demand/Response
BEMS	Building energy management system

1 Introduction

1.1 Aims and objectives

The aim of this report, titled "Requirements: Key Performance Indicators, system components and performance targets", is to present the outcomes of task 1.5 about "Key Performance Indicators (KPIs)".

The focus of the activity and of the document is on the definition and identification of a small number of KPIs to ensure a proper assessment of the impact of HYBUILD solutions in light of the main objectives of the project as reported in the Description of Action (DoA). Starting from a three-level hierarchical structure of the two innovative hybrid storage solutions (for Mediterranean and continental climates, respectively), first a set of relevant Performance Indicators (PIs) proposed by partners for each level are reported and classified. Then, based on their expertise and the main objectives of the project, 7 KPI are selected and extensively described with a special focus on the application scenarios considered in the project.

1.2 Relations to other activities in the project

The outcomes of this task will be mainly used in:

- WP4 to evaluate through dynamic simulations the performance of the overall building system considering the two-hybrid storage concept proposed in HYBUILD.
- WP6 to evaluate the performance of the installed system in the three demo-cases using the monitoring data and possibly, when available, comparing the results with the pre-refurbishment actions.

1.3 Report structure

The document is composed of the following sections:

- **Section 1** presents the aim and objectives of the task associated with the report, the relationship with the other activities in the project, the partner contributions and includes the present outline.
- **Section 2** recalls the HYBUILD system structure defining the different levels in which performance indicators (PI) will be evaluated (component/module, hybrid sub-system and overall building system).
- **Section 3** describes briefly the general methodology adopted to identify and classify the PIs. An introduction to the rationale underlying the selection of KPIs with respect to the specific request of the project call targets will be also provided.
- **Section 4** reports all the PIs collected related to TES, electric energy storage, hybrid sub-system and the overall building system. The PIs for the overall building system are divided into different groups (i.e. energy, environmental, comfort, economic). The PIs are not presented as a simple list, but rather using tables to show clearly PI definition, unit of measure, and possible references.
- **Section 5** after a short introduction where the seven KPIs identified at consortium level are listed and linked to project objectives, there is a sub-section dedicated to each of them where it is reported: definition, evaluation techniques and level of applicability (i.e. component/module, sub-system, system building).
- **Section 6** describes four additional PIs required to evaluate the impact of the project.
- **Section 7** concludes the report.

1.4 Contributions of partners

Below, the partners who collaborated to this report writing are listed and a brief description of their contribution is provided.

- **EURAC** led the activities of this task and the deliverable writing. They collected and organized all the contributions and defined the electric storage and energy PIs and KPIs about seasonal energy performance and renewable energy.
- **STESS (RINA-C as third party)** as leader of WP1, supported the activities in this task and the deliverable writing. They contributed in particular to the definition of environmental PIs and on the KPI related to energy savings and CO2 emission reduction.
- **UDL,** due to their experience and extensive work on thermal energy storage system (TESS), contributed to the PIs related to TESS and to the "new" definition of the Thermal storage energy density KPI.
- **UCY** supported EURAC on the definition of electric storage and energy PIs.
- **COMSA** defined the PIs related to the economic aspects, included the KPIs related to return on investment and payback-time.
- **ENG** proposed the new KPI about flexibility in terms of Demand response and introduced PIs related to the optimized control of building energy management system.
- **NTUA** collected the PIs related to thermal comfort into the building.
- **NBK** contributed to the compactness KPIs section and PIs related to installation.

2 HYBUILD systems structure

The goal of the HYBUILD project is the development of two innovative concepts of hybrid storage: one dedicated to the production of cooling energy for Mediterranean countries and the other mainly dedicated to the delivery of heating energy for continental countries, as shown in Figure 1. From the structural point of view the two systems considered in the project, consist of three different levels, which (from the lowest to the highest) are summarized below.

- The core **components/modules (L1)** are the individual sorption thermal storage, high density latent thermal storage, DC controller (coupled with the compression Heat-Pump - HP) and electrical storage adopted to implement the Mediterranean or continental concept.
- For **hybrid storage sub-systems (L2),** we mean the proper combination of multiple L1 core components/modules. In particular, HYBUILD proposes two innovative sub-systems:
    - One composed by low temperature latent storage, DC-driven HP, sorption storage, electrical storage and DC controller for Mediterranean climates;
    - One consisting of high temperature latent storage for Domestic Hot Water (DHW), DC-driven HP, electrical storage and DC controller for continental climates.
- The **overall building system (L3)** is based on the inclusion of the L2 sub-systems considering also the renewable solar generation (from photovoltaic and/or solar collectors), the sensible water storage (for the continental climate) and the building energy management system.

In Figure 1 components/modules are indicated with numbers, while sub-systems are enclosed within dashed green rectangles for both the Mediterranean and continental cases.

In the following Sections, the listed PIs are classified on the basis the HYBUILD system structure, depending on the level they are applied to.

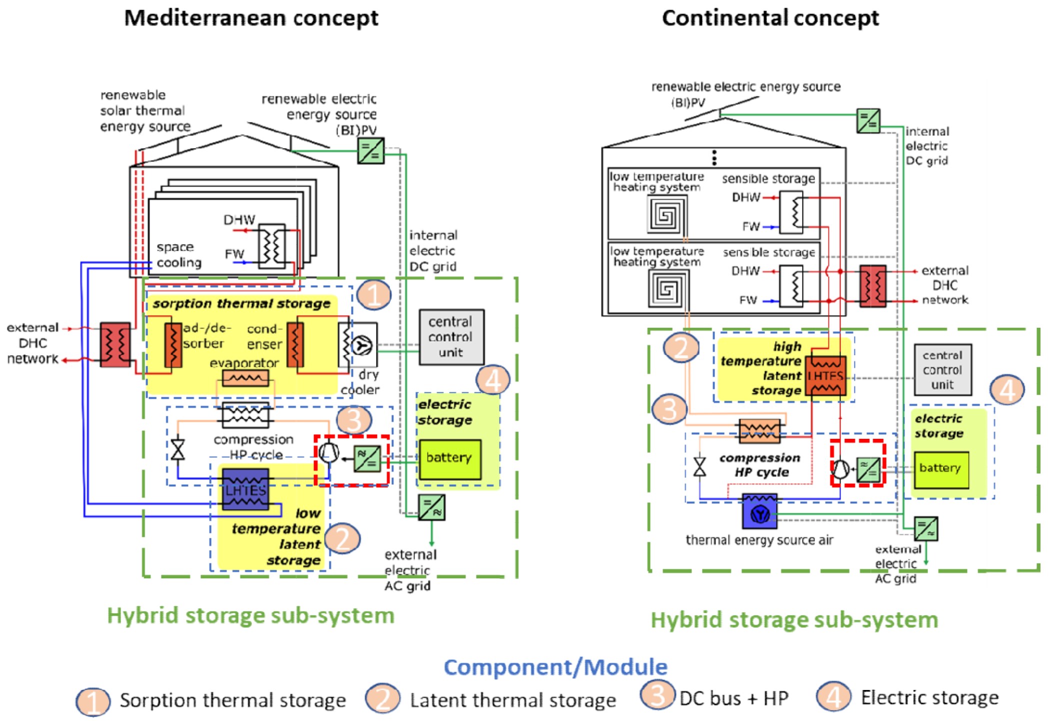


Figure 1 - Schematic of the hybrid storage concept integrated in the building for Mediterranean climate during summer operation and Continental climate during winter operation

3 Methodological approach

In general, PIs must be closely related to project's goals and provide means for the measurement and management of the progress towards such goals for further learning and improvement. PIs are defined to measure the performance of a system/process and to provide easily accessible and useful information about system/process and their parts.

PI selection relies upon a good understanding of what is important to a given application or technology. Extensively used in business and financial contexts, PIs are acquiring more importance also for technical assessments and to evaluate sustainability. A well-defined PI should have the following characteristics [1]:

- **Uniqueness:** it should have a single definition in order to not generate confusion or misunderstanding.
- **Measurability:** It should have a quantitative value, or when this cannot be applied, it must still be measurable with clear, concise measurement attributes.
- **Applicability**: it should be used not only in specific cases, sizes and processes, but also in a wide range of applications.
- **Relevance**: it should be meaningful enough to the purposes of the system and specific to the characteristics of its processes and components.

Another general feature is that, all terms uses to compute the PI must be referred to the same activity/item and to the same time period (e.g. year, month, hour, …). Based on these general criteria, almost 40 PIs have been proposed by project partners to characterize the technical performance of components/modules (L1) and sub-systems (L2). To evaluate the overall building system (L3) a different PI classification has been performed, i.e. related to energy, comfort, environmental, and economic aspects. In Section 4, for each PI the following information will be reported, i.e.

- **Indicator name**;
- **Definition**, with some explanation about how the PI is calculated;
- **Unit of measurement**;
- **Application level** (i.e. building, sub-system or component/module).

While the proposed PIs are useful for a fine-grained technical performance evaluation of multiple heterogeneous aspects of the HYBUILD solutions, just a limited number of them can be regarded as "key" for the evaluation of project objectives and, above all, to assess the impact of HYBUILD outcomes. In this respect, the consortium has identified and selected 7 KPIs, following partially the methodology provided in [2], starting from the main objectives of the project. Such objectives, briefly outlined below, are reported in more detail in Section 5, where also the KPI target values are specified, including:

- Cost effective overall energy storage solutions supported by advanced economic and business models;
- Market penetration with high replicability potential of robust hybrid storage solutions;
- Increased share of renewable energy sources;
- Easy-to-integrate and compact solutions for existing buildings/systems;
- Superior energy performance of heating and cooling systems and enhanced energy system flexibility;
- Reduction of building energy consumption and greenhouse gases emissions.

4 Collected Performance Indicators (PIs)

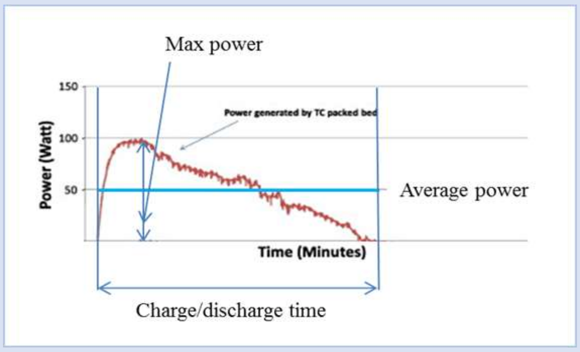
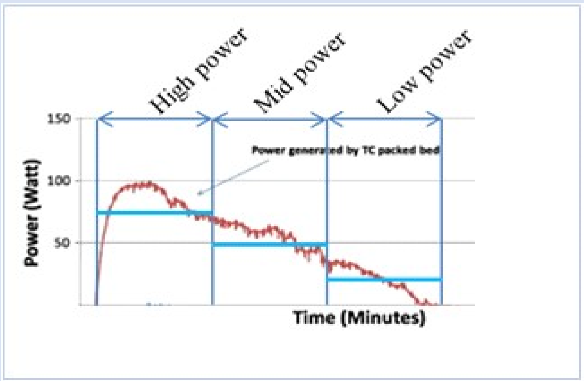
4.1 Components/Modules PIs (L1)

4.1.1 Thermal Energy Storage

Most of the thermal energy storage PIs presented in this section are defined within Annex 30 - "Thermal Energy Storage for Cost-Effective Energy Management and CO_2 Mitigation" [3], which is an annex of the International Energy Agency's implementing agreement Energy Conservation through Energy Storage (ECES). The PIs listed in the following mainly characterize the technical performance of the thermal storage in order to evaluate the improvement achieved in terms of thermal energy density, response time and packing factor. Indeed, in HYBUILD it is supposed to achieve an increase of the energy thermal storage density five times higher than water, higher stability with high number of cycles and a sensitive reduction of volume.

Table 1 - Performance Indicators related to thermal energy storage system

PIs	Definition	Units	References
Nominal power	The nominal power level refers to the heat flux between the process and the system. It is measured with five different values for both the charge and discharge (for a total of ten parameters). They are: • *Maximum power and Average power*	[W]	[3], [4]

	 • *High/mid/low power* 		
TES density	$$ED_{sys} = \frac{ESC_{sys}}{V_{sys}}$$ ESC_{sys} system energy storage capacity V_{sys} system volume, intended of thermal storage	[J/m^3] or [kWh/m^3]	[3], [5]
Response Time	The response time ($ReTi_{sys}$) is the interval of time between the moment when the charge or the discharge order is set and the moment when the TES system reaches its average nominal power ($Q_{av.sys}$).	[min]	[3], [4]
Efficiency	$$\varepsilon_{sys.xh} = \frac{\lvert Q_{sys.discharge}\rvert}{\lvert Q_{sys.charg}\ \rvert + \lvert Q_{sys.aux}\rvert}$$ $Q_{sys.discharge}$: Heat delivered to the heat sinks during the discharge [J]. $Q_{sys.charge}$: Heat absorbed from the heat sources during the charge [J]. $Q_{sys.aux}$: Heat provided by the components of the system [J].		[3], [4]
Auxiliary energy ratio	$$\mathrm{Aux}_{sys} = \frac{\sum E_{aux.sys}}{\lvert Q_{sys.discharge}\rvert}$$	[J·J$_{th}^{-1}$] or [kWh·kWh$_{th}^{-}$	[3] , [4]

	Where: $Q_{sys.discharge}$: Heat delivered during discharge phase [J_{th}] or [kWh_{th}]. $\sum E_{aux,sys}$: Energy consumed by all the components of the system during the standby, charge, storage and discharge phases (full cycle of the TES system) [J].	[1]	
Minimum cycle length	$$MinCy_{sys} = \frac{ESC_{sys}}{P_{nom.sys.charge}} + \frac{ESC_{sys}}{P_{nom.sys.discharge}}$$ ESC_{sys}: System energy storage capacity [J] $P_{nom.sys.charge}$: Nominal power for charge [W] $P_{nom.sys.discharge}$: Nominal power for discharge [W]	[s] / [h] / [d]	[3], [4]
Packing factor	$$PF = \frac{V_{TES\ material}}{V_{TES\ system}}$$ $V_{TES\ material}$: actual volume of TES material in the TES system [m^3] / [L]. $V_{TES\ system}$: maximum volume of TES material that the TES system can contain [m^3] / [L].		[3] , [4]
TES flexibility	It is a "yes/no" parameter, indicating whether partial charge or discharge is possible.		[6]

4.1.2 Electric storage and DC controller

In HYBUILD, the electric storage is a battery based on lithium-titanate (LTO) chemistry. The choice has been done considering high cycling rate, long life and safety in order to assure proper behaviour during several years operate in residential building environment. According to this, in the following, some technical PIs to evaluate the efficiency and durability of the battery are listed. Moreover, because the electrical power in HYBUILD will be mainly transmitted and driven using a DC bus, which is supposed to decrease the losses and increase the conversion efficiency. This PI is also included in the following table.

Table 2 - Performance Indicators related to Electric energy storage systems

PIs	Definition	Units	References
Storage capacity	It is possible to diversify between: *Total capacity*, which (C_{BESS}) represents the total energy that can be stored at reference condition. *Maximum useful capacity* ($C_{u\text{-}max}$), is the maximum energy that can be retrieved at	[Wh]	[7]

	reference condition without negatively affecting the storage system (i.e. permanent damages), noted $C_{u\text{-}max}$		
Maximum charging/discharging power	The maximum charging and discharging power which can be absorbed / released by / from the battery for the minimum charging and discharging periods	[kW]	[7]
Durability	The maximum number of working cycles (NCt) during which the storage system can release at least 80% of the designed useful capacity, during its lifetime in years	[NCt]	[7]
Charging/discharging efficiency	$\eta_C = \frac{C_{BESS} \cdot DoD}{C_r}$ $\eta_D = \frac{C_{U-max}}{C_{BESS} \cdot DoD}$ Where C_r is the recharged energy to reach 100% of BESS capacity, DoD is the dept of discharge and C_{BESS} is the storage capacity		[7]
Conversion efficiency ratio	This PI is related to the use of DC bus $\eta_{sav} = \eta_{DC}/\eta_{AC}$ $\eta_{DC} = \frac{P_{out}}{P_{in\_DC}}$ $\eta_{AC} = \frac{P_{out-AC}}{P_{in\_AC}}$ where P_{out} and P_{in} are the power output and power input for DC and AC system	[%]	

4.2 Mediterranean and Continental hybrid sub-systems PIs (L2)

The core components/modules proposed in HYBUILD are combined to create a sub-system level able to provide heating or cooling depending to the case. These sub-systems are indeed different for the Mediterranean and the continental concepts. In particular, it is highlight that the Mediterranean sub-system is optimized for cooling, when the continental for heating and DHC. However, both of them have similar objectives in terms of technical performance:

- Reduce the number of components with respect to similar system which provide heating/cooling/DHW
- Enhance the coefficient of performance (COP) or the energy efficiency ratio (EER).
- Modular design and flexible heat transfer control to increase the range of applications.

Table 3 - Performance Indicators related to Hybuild sub-systems

PIs	Definition	Unit	References
Seasonal coefficient of performance	$SCOP_{SH} = {Q_{SH}}/{E_{SH}}$		[8], [9]

	$$SCOP_{DHW} = {Q_{DHW}}/{E_{DHW}}$$ where: Q is the demand of heating (SH) or DHW E is the electric energy to cover the demand		
Seasonal energy efficiency ratio	$$SEER_{SC} = {Q_{SC}}/{E_{SC}}$$ where: Q_{SC} is the cooling demand E_{SC} is the electric energy to cover the demand		[8], [9]
Seasonal Performance Factor	Considering the whole sub-system concept, this PI can be defined for both electrical and thermal energy: $$SPF_{el} = \frac{Total\ delivered\ energy}{Total\ consumed\ electricity}$$ $$SPF_{th} = \frac{Total\ delivered\ energy}{Total\ consumed\ thermal\ energy}$$ SPF is evaluated yearly		[8], [9]
Compactness of sub-system	Two different PIs can be defined for compactness referred to Mediterranean or Continental sub-system: $$\frac{V_{SS\_M}}{E_{cool}} \qquad \frac{V_{SS\_C}}{E_H+E_{DHW}}$$ Where V_{SS_M} and V_{SS_C} are the volume of the Mediterranean and Continental sub-system respectively and $E_{cool\ H,DHW}$ is the energy required for cooling, DHW and heating during the year.	[m^3/kWh]	

4.3 Overall Building Systems PIs (L3)

In this section, the main PIs identified at overall building level have been listed, using the following sub-categories:

- Energy related PIs;
- Environmental related PIs;
- Comfort related PIs;
- Installation related PIs.
- Economic relates PIs;

4.3.1 Energy related PIs

First of all, the energy performance of the overall building system should be taken into account and evaluated covering both consumption and production aspects. The PIs listed below will be focused on:

- building demands (both electrical and thermal);
- space heating and cooling and DHW generation;
- solar photovoltaic generation;
- solar thermal energy.

Table 4 - Performance indicators related to energy behaviour for the overall building system

PIs	Definition	Unit	References
Demand Factor	$D_F(t) = \frac{Demand}{Maximum\ possible\ demand}$ It is a time dependent quantity, so it can be evaluated over different time interval (e.g. day, month, year). This index can be used for both thermal and electrical demand		[10]
Annual heating and cooling demand per net useful area	$Q_t = \frac{Q_{th}}{A}$ Where Q_{th} is the thermal demand and A is the considered area. It can be evaluated over a month or year.	$\left[\frac{kWh}{m^2}\right]$	[10]
Final energy use	For electricity driven systems, the final energy (*FE*) equals the electricity used to drive the HVAC systems, while for gas or biomass driven ones, the FE equals the Higher Calorific Value of the used fuel by its mass consumption (FE_{fuel}). The FE for DHC supply thermal energy from the networks	[kWh]	[8]
Primary energy use	$PE = FE * PEf_{ec}$ Where PEf_{ec} is the Primary Energy Factor which the value depends from the calculation method and inclusion or not of renewable. In HYBUILD it is consider including all non-renewable source. Values of this factor varies for energy carrier (ec)		
Primary energy ratio	Defined as the ratio of the useful energy output to primary input.		[11], [12]

	$$PER = \frac{useful\ energy}{primary\ energy\ (PE)}$$ PE can include or not renewable		
Thermal efficiency	$$\eta_{SH} = {Q_{SH}}/{FE_{fuel,SH}}$$ $$\eta_{DHW} = {Q_{DHW}}/{FE_{fuel,DHW}}$$ Where: Q is the heat or DHW demand and FE_{fuel} is the energy entailed in the fuel consumed		[8]
Seasonal Performance factor	$$SPF_{el} = \frac{Total\ delivered\ energy}{Total\ consumed\ electricity}$$ $$SPF_{th} = \frac{Total\ delivered\ energy}{Total\ consumed\ thermal\ energy}$$ The total output and input are in kWh/y		[8], [9]
Solar fraction	$$SF_{tot} = \frac{(Q_{ST,DHW} + Q_{ST,SH} + Q_{ST,SC})}{(Q_{DHW} + Q_{SH} + Q_{SC})}$$ Where $Q_{ST,DHW}$, $Q_{ST,SH}$ and $Q_{ST,SC}$ is the net solar thermal energy employed for DHW uses and space heating and cooling (in the case of the adsorption chiller).		[8]
Target yield – PV system	$$PR = \frac{Y_f}{Y_s}$$ Where Y_f is the ratio of utilizable AC electricity and Ys is the amount of energy that could be generated if modules were operated under standard test conditions (STC)	[%]	[13]
Annual electricity PV production	$$E_{PV} = A \cdot r \cdot H \cdot PR$$ where: A is the solar panel area (m^2), H is the annual average solar radiation on tilted panels (kW/m^2), PR is the performance ratio, r is the solar panel yield or efficiency (%)	[kWh]	
Energy savings	The energy saving indicator is calculated, in terms of Primary energy as presented in the following equation: $$PEsav_t = \frac{PE_{hy} - PE_r}{PE_r} \quad [\%]$$ Where $PE_{hy}\left[\frac{kWh}{year}\right]$ is the total primary energy		

	consumed after HYBUILD implementation. $PE_r\left[\frac{kWh}{year}\right]$ is the total primary energy consumed in the reference case. In order to calculate the emissions reduction it is important also to define final energy savings for each energy carrier, described in the following equation: $$FEsav_{ec} = FE_{hy,ec} - FE_{r,ec}$$ where $FE_{hy,ec}$ is the final energy consumption of the energy carrier ec after the HYBUILD solution implementation. $FE_{r,ec}$ is the final energy consumption of the energy carrier (ec) of the reference case.		
Self-consumption (SC)	Defined for electric or thermal (el,th) energy as: $$SC_{(el,th)} = \frac{E_{RES(el,th)}}{E_{RES-TOT(el.th)}}$$ Where: $E_{RES(el,th)}$ is the renewable energy directly consumed or stored into the storages $E_{RES-TOT(el,th)}$ is the total production	[%]	[14]
Self-sufficiency (SS)	Defined for electric or thermal (el,th) energy $$SS_{(el,th)} = \frac{E_{RES(el,th)}}{E_{D(el.th)}}$$ Where: $E_{RES(el,th)}$ is the renewable energy directly consumed or stored into the storages $E_{D(el,th)}$ is the total demand	[%]	[14]
Share of renewables	Share of renewables based on final energy consumption		[7]

	$$SR_{(el,th)} = \frac{E_{RES*(el,th)}}{E_{D(el.th)}}$$ Where $E_{RES*(el,th)}$ include the energy consumed on-site, stored and from grid energy mix		
Solar thermal system efficiency	$$\eta_{ST} = {Q_{ST,store}}/{I_{coll}}$$ The energy delivered to the solar thermal energy storage ($Q_{ST,store}$) is considered, accounting for all the irradiation incident on the collector plane (I_{coll}) when the solar pump is running or during stagnation periods. This PI is for Fresnel solar collectors.		[8]
Global daily energy reduction	$$GDER = ED_{reference} - ED_{optimised}$$ It is referred to the control implemented in the BEMS and it evaluates the difference between the energy demand (ED) required by the reference system to ED required by the optimised system	[kWh]	New
Flexibility	Demand Response Power Tracking (DRPT) $$DRPT = 1 - \frac{\sum_{i=1}^{n} \lvert E_{Response,i} - K_{CL} E_{Demand,i} \rvert}{\sum_{i=1}^{n} E_{Response,i}}$$ $$K_{CL} = \frac{\sum_{i=1}^{n} E_{Response,i}}{\sum_{i=1}^{n} E_{Demand,i}}$$ where: n is the number of timestamps of the interested time horizon; $E_{Response,i}$ is the energy behaviour of the controlled system in that i[th] timestamp; $E_{Demand,i}$ is the desired energy behaviour request in that i[th] timestamp; K_{CL} is the indicator of the contribution level the building may provide, calculated as normalisation factor to compare the two profiles. Flexibility Capacity Index (FCI) $$FCI = \frac{\sum_{i=1}^{n} \lvert E_{typical,i} - E_{optimized,i} \rvert}{n\, E_{typical,i}}$$ Where:		New

	$E_{typical,i}$ is the typical energy behaviour of the system in that ith timestamp. $E_{optimized,i}$ is the optimized energy behaviour of the system in that ith timestamp.		

4.3.2 Environmental related PIs

The first performance indicator identified is related to the carbon dioxide (CO_2) emissions of the HYBUILD solutions. Carbon dioxide is the primary greenhouse gas emitted through uman activity. The combustion of fossil fuel is the main human activity related to the CO_2 emissions (1) and it is thus a very important indicator to evaluate the energy efficiency and the environmental impact of heating and cooling systems.

Another important indicator is related to the greenhouse gases (GHG) emissions. Greenhouse gases constitute a group of gases contributing to global warming and climate change. The Kyoto Protocol, an environmental agreement adopted by many of the parties to the United Nations Framework Convention on Climate Change (UNFCCC) in 1997 to curb global warming, nowadays covers seven greenhouse gases [16]. Three are non-fluorinated gas: Carbond dioxided, Methane (CH_4) and Nitrous oxide (N_2O). The other four gases are fluorinated gas: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6)and nitrogen trifluoride (NF_3). Converting them to CO_2 equivalent makes it possible to compare them and to determine their individual and total contributions to global warming.

Ather three indicator referring to air pollutants have been identified: Nitrogen Oxides (NO_x) emission, Sulphur dioxide (SO_2) emission and level of the fine particles PM2.5.

The Nitric oxide (NO) and nitrogen dioxide (NO_2) are together referred to as nitrogen oxides. Combustion of fossil fuels is by far the dominant source of NO_x emissions. NO_x contributes to acid deposition and eutrophication which, in turn, can lead to potential changes occurring in soil and water quality [17] NO_2 in particular is associated with adverse affects on human health, as at high concentrations it can cause inflammation of the airways.

The Sulphur dioxide is emitted when fuels or other materials containing sulphur are combusted or oxidised. The largest sources of SO_2 emissions are from fossil fuel combustion at power plants andother industrial facilities [18]. SO_2 is used as indicatior for the larger group of gaseous sulfur oxides (SO_x), which are found in the atmosphere at concentrations much lower than SO_2.

The PM2.5, or fine particles, indicates the particulate matter with diameter of 2.5 micrometres or less. They can remain airborne for long periods and travel hundreds of miles. The effects of chronic PM exposure on mortality (life expectancy) seem to be attributable to PM2.5 rather than to coarser particles [19]. Epidemiological and toxicological studies have shown that PM2.5 does not only induce cardiopulmonary disorders and/or impairments, but also contributes to a variety of other adverse health effects, such as driving the initiation and progression of diabetes mellitus and eliciting adverse birth outcomes.

In the following table the definitions for calculating the environmental indicators described before are presented.

Table 5 - Performance indicators related to environmental behaviour for the overall building system

PIs	Definition	Units	References
CO_2 emission savings	$CO2_{hy,t} = \sum_{ec} FE_{hy,ec} * CO2emf_{ec}$ where $CO2emf_{ec}$ $\left[\frac{tCO2eq}{kWh}\right]$ is the CO_2 emission factor of the energy carrier (ec) for the specific Country $FE_{hy,ec}$ $\left[\frac{kWh}{year}\right]$ is the final energy consumption of the energy carrier (ec) after implementing the HYBUILD solutions. CO2 emissions savings $tCO2sav_t = \sum_{ec} FEsav_{ec} * CO2emf_{ec}$ $FEsav_{ec}$ $\left[\frac{kWh}{year}\right]$ is the final energy saving of the energy carrier (ec);	$\left[\frac{tCO_2eq}{year}\right]$	
GHG emissions	$GHG_{hy,t} = \sum_{ec} FE_{hy,ec} * GHGemf_{ec}$ Where $GHGemf_{ec}$ $\left[\frac{tCO2eq}{kWh}\right]$ is the GHG emission factor of the energy carrier ec; GHG emissions savings $GHGsav_t = \sum_{ec} FEsav_{ec} * \mathrm{GHG}emf_{ec}$	$\left[\frac{tCO2eq}{year}\right]$	[16], [20]
NO_x emissions	$tNOx_{hy,t} = \sum_{ec} FE_{hy,ec} * NOxemf_{ec}$ where $NOxemf_{ec}$ $\left[\frac{tNOxeq}{kWh}\right]$ is the NO_x emission factor of the energy carrier ec. NOx emissions savings $tNOxsav_t = \sum_{ec} FEsav_{ec} * NOxemf_{ec}$	$\left[\frac{tNOxq}{year}\right]$	[17]
SO_2 emission	$tSO2_{hy,t} = \sum_{ec} FE_{hy,ec} * SO2emf_{ec}$ Where $SO2emf_{ec}$ $\left[\frac{tSO2eq}{kWh}\right]$ is the SO_2 emission factor of the energy carrier ec.	$\left[\frac{tSO_2q}{year}\right]$	[20], [18]

	SO$_2$ emissions savings $tSO2sav_t = \sum_{ec} FEsav_{ec} * SO2emf_{ec}$		
PM2.5 emissions	$PM2.5_{hy,t} = \sum_{ec} FE_{hy,ec} * PM2.5emf_{ec}$ where $PM2.5emf_{ec}\left[\frac{tPM2.5e}{kWh}\right]$ is the PM2.5 emission factor of the energy carrier ec. PM2.5 emission savings $PM2.5sav_t = \sum_{ec} FEsav_{ec} * PM2.5emf_{ec}$	$\left[\frac{tPM2.5eq}{year}\right]$	

4.3.3 Comfort related PIs

Several environmental parameters affect human thermal comfort inside building spaces. The seven psychrometric parameters that can be directly measured are:

- Air temperature T_a
- Wet bulb temperature T_{wb}
- Dew point temperature T_{dp}
- Water vapor pressure P_a
- Total atmospheric pressure P_t
- Relative humidity rh
- Humidity ratio W_a

Two other important parameters include air velocity V and mean radiant temperature T_r. The latter is the temperature of an exposed surface in the environment. The temperatures of individual surfaces around the surface are usually combined into a mean radiant temperature T_r. Finally, globe temperature T_g, which can also be measured directly, is a good approximation of the operative temperature T_o and is also used with other measurements to calculate the mean radiant temperature.

The above environmental variables together with other secondary factors influence the comfort feeling that can be quantified and predicted in several ways:

Table 6 - Performance indicators related to thermal comfort for the overall building system

PIs	Definition	Units	References
Thermal sensation	ASHRAE thermal sensation scale divides thermal comfort (Y) in 7 levels (hot = 3, warm = 2, slightly warm = 1, neutral = 0, slightly cool = -1, cool = -2, cold = -3) $Y(T_a, P_a)$ is function of gender and exposure period (in hours) and depends by T_a*[°C]* is the air temperature and		[21]

	P_a *[kPa]* is the water vapor pressure		
Thermal complaints (h:hot, l:cold)	$$v_h = \frac{1}{2\pi}\sqrt{\frac{{\sigma_{\dot{T}_H}}^2 + {\sigma_{\dot{T}_S}}^2}{{\sigma_{T_H}}^2 + {\sigma_{T_s}}^2}}\exp\left(-\frac{1}{2}\frac{\left(\mu_{T_s} - \mu_{T_H}\right)^2}{{\sigma_{T_H}}^2 + {\sigma_{T_s}}^2}\right)$$ $$v_l = \frac{1}{2\pi}\sqrt{\frac{{\sigma_{\dot{T}_L}}^2 + {\sigma_{\dot{T}_S}}^2}{{\sigma_{T_L}}^2 + {\sigma_{T_s}}^2}}\exp\left(-\frac{1}{2}\frac{\left(\mu_{T_s} - \mu_{T_L}\right)^2}{{\sigma_{T_L}}^2 + {\sigma_{T_s}}^2}\right)$$ Where σ denotes standard deviation and μ mean value T_s: space temperature, $\dot{T}_s$: rate of change of space temperature	#of complaints /m²	[21]
Predicted Mean Vote	Follows the ASHRAE thermal sensation scale $$PMV = (0.303e^{-0.36\cdot M} + 0.028)\cdot L$$ where M: metabolic rate, L: heat loss from human body		[21]
Predicted Percent Dissatisfied	$$PPD = 100 - 95e^{-(0.03353\cdot PMV^4 + 0.2179\cdot PMV^2)}$$	% persons dissatisfied	[21]

4.3.4 Installation related PIs

The solutions proposed in HYBUILD both in terms of components/modules or sub-systems are requested to have characteristics as the easiness for the installation and compactness in order to be widely installed and deployed in residential buildings. These characteristics are not obvious to be defined and quantified and no common PI exist (at least in our knowledge). Since the space or volume required for technical installation of HVAC system, storage or renewable generation Is limited to the considered building/context the installation PIs should be referred to the overall system building level. The aim, when possible, is to compare the HYBUILD solution using the proposed PIs listed in Table 8 with systems for heating and cooling which exhibits similar performances.

Table 7 - Performance indicators related to installation easiness for the overall building system

PIs	Definition	Units	References
Easiness for electrical or thermal installation	$$e_{in} = \frac{L}{A}$$ where L is the length of electrical cables (or pipes) to be installed and A is the living area	$[m/m^2]$	
Complexity of the whole system installation	Number of equipment to be connected		
Compactness of the overall technical	$$\frac{V_{HP} + V_{PCM\ sto} + V_{W\ sto} + \cdots}{E_{Heat} + E_{Cool} + E_{DHW}}$$	$[m^3/kWh]$	

system	V_{HP} is the volume occupied by the heat pump $V_{PCM\ sto}$ is the volume occupied by the pcm storage unit $V_{W\ sto}$ is the volume occupied by the water storage unit E_{Heat} is the yearly heating energy needed in kWh/year E_{Cool} is the yearly cooling energy needed in kWh/year E_{DHW} is the yearly energy needed for DHW production in kWh/year		

4.3.5 Economic related PIs

In order to create a solution that could be sold in the market, it is also critical to track the economic potential of the solution. More details on these performance indicators are described in the KPI descriptions in section 5.7.

Table 8 - Performance indicators related to economic aspects for the overall building system

PIs	Definition	Units	References
Return on investment	$ROI = \frac{Gain\ from\ Investment - Investment\ Cost}{Investement\ Cost}$ $Investment\ Cost\ = C_{eq} + C_{en} + C_l + C_f$ C_{eq}: cost of all developed sub-system C_{en}: engineering cost C_l: labor and installation cost C_f: financing costs related to installation $Gain\ from\ Investment\ (GI) = \sum_{h=1}^{T*8760}(CPE_{sav} + DR)$ CPE_{sav}: energy cost of primary energy savings DR: demand/response remuneration		
Net present value	$NPV = \sum_{t=1}^{T} \frac{GI}{(1+r)^t} - C_o$	[years]	

	GI is the gain from investment as defined in ROI C_o is the investment cost as defined in ROI *t* is the current time period *T* is the total number of years in the time period considered *r* is the discount rate (which should be based on available investment and/or inflation)		
Payback period	It is the year *T* in which the NPV equals 0. Simple payback period is the year *T* when NPV equals 0 assuming *r* is set to 0.	[years]	
Potential market size of the solution	To calculate the potential market for the solution, it is important to include not only the energy cost savings ($EC_{sav} = EC_{ref}-EC_{HYBUILD}$), but also the potential business models with flexibility (considering the available flexibility of the solution), renewable energy credits and any additional alternative revenue streams developed in the solution.		D7.4 [HYBUILD]

5 Key Performance Indicators for HYBUILD

Following the methodology described in Section 3 and considering the HYBUILD main objectives listed in the Table below, the KPIs selected by the project partners are:

- KPI.1 – Thermal Energy Storage Density;
- KPI.2 – Seasonal Energy Performance;
- KPI.3 – Share of renewable and self-consumption;
- KPI.4 – Energy savings and CO_2 emission savings;
- KPI.5 – Compactness;
- KPI.6 – Flexibility;
- KPI.7 – Return on Investment.

In addition, the rightmost column of the Table highlights the level (i.e. component/module – L1, sub-system – L2, and overall building system – L3) at which each KPI is applied.

Table 9 - Relevant KPIs with the corresponding HYBUILD objectives

	HYBUILD objectives	KPI	Application level
1	*Increase of thermal energy storage density*	**KPI.1**	**L1**
2	*Expected energy and CO_2 emissions reduction ranging from 20% to 40% depending on the configuration and contexts;*	**KPI.2, KPI.3, KPI.4**	**L2 – L3**
3	*Increase of seasonal performance of the heating and cooling system*	**KPI.2**	**L2 – L3**
4	*Easy to integrate and compact solutions into*	**KPI.5**	**L1 - L2 - L3**

	existing building		
5	*ROI of 8 years for building non-connected to DHC and 15 years for buildings connected to DHC*	**KPI.7**	**L3**
6	Superior energy performance contributing also to the energy system flexibility	**KPI.6**	**L3**

5.1 Thermal Energy Storage Density

The thermal energy density ($ED_{thermal}$) is a KPI that measures the amount of thermal energy that can be stored in a certain available volume. It is usually measured in $J \cdot m^{-3}$ or $kWh \cdot m^{-3}$, but any other units for energy per volume can be used. There are two different levels at which $ED_{thermal}$ can be calculated: material- and system levels. In order to avoid confusion and to be consistent, it is specified that in this paragraph when it is referred to system level it means the thermal energy storage level, which correspond to the component/module (L1) level of the general HYBUILD structure provided in Section 2.

The energy density at material level (ED_{mat}) only considers the TES material, without any other component, and takes into account the material thermophysical properties. On the other hand, the energy density at system level (ED_{sys}) considers the impact of all the components of the system. The value of this KPI is affected by the type of TES material used (sensible, latent, chemical or sorption) and also by the operation conditions of the system (mainly temperatures). Despite that fact that in practice the real TES capacity is lower than the theoretical maximum (fully charged or discharged), a simplified definition is used to demonstrate the overall concept of the energy density calculation.

In this section, the equations allow calculating the energy density at the material level and provide a conceptual guide for calculating it at system level for the three storage technologies: sensible heat, latent heat, and storage based on sorption and chemical reactions (usually known as thermochemical energy storage).

At material level, the thermal energy density (ED_{mat}) takes into account the storage capacity of the TES material based on its thermo-physical properties and the operation conditions of the system.

The energy density of sensible heat TES materials ($ED_{mat,sens}$) is calculated as a function of their specific heat, minimum density, and operation temperature range as shown in Eq. 1:

$$ED_{mat,sens} = c_{p.mat} \cdot \rho_{min.mat} \cdot \Delta T_{op} \qquad \textbf{Eq. 1}$$

where $c_{p.mat}$ [$kJ \cdot kg^{-1} \cdot K^{-1}$] is the average specific heat and $\rho_{min.mat}$ [$kg \cdot m^{-3}$] is the minimum density, both being measured in the operation temperature range (ΔT_{op}). The operation temperature range (ΔT_{op}) refers to the nominal temperature conditions at which the material will be maintained during the operation of the system and are comprised between a minimum temperature (T_{min}) and a maximum temperature (T_{max}). The minimum density of the material ($\rho_{min.mat}$) in the operation temperature range of the system is considered because it corresponds to the maximum volume occupied by the material.

The energy density of latent heat TES materials ($ED_{mat,lat}$) takes into account the energy stored during phase change but also the part of sensible heat in both solid and liquid phases covered within the operation temperature range. Therefore, it is calculated as shown in Eq. 2:

$$ED_{mat,lat} = \left(c_{p.mat.s} \cdot \Delta T_s + \Delta H_{pc} + c_{p.mat.l} \cdot \Delta T_l\right) \cdot \rho_{min.mat} \qquad \textbf{Eq. 2}$$

where $c_{p.mat.s}$ and $c_{p.mat.l}$ are the average specific heats at the solid and liquid states [kJ·kg^{-1}·K^{-1}], respectively, ΔH_{pc} is the specific melting enthalpy [kJ·kg^{-1}], $\rho_{min.mat}$ is the minimum density in the operation temperature range, ΔT_s [K] is the temperature variation in the solid phase (the difference between the lowest temperature of the phase change range and T_{min}), and ΔT_l [K] is the temperature variation in the liquid phase (the difference between T_{max} and the highest temperature of the phase change range). The relation between the different temperature ranges is shown in Eq. 3:

$$\Delta T_{op} = \Delta T_s + \Delta T_{pc} + \Delta T_l \qquad \text{Eq. 3}$$

where ΔT_{pc} [K] is the phase change. The $TED_{mat,lat}$ is calculated with either the temperatures of the heating or the cooling phase change curves to avoid any hysteresis effects of the material.

The energy density of TES materials based on sorption and chemical reactions ($ED_{mat,tc}$) is calculated taking into account the equation proposed by [22], which is modified to implement the concept of minimum density, as shown in Eq. 4:

$$ED_{mat,tc} = \frac{|\Delta H^0_{n\to m}| \cdot (n-m)}{M_n} \cdot \Delta x \cdot r \cdot \rho_{min.mat} \qquad \text{Eq. 4}$$

where $\Delta H^0_{n\to m}$ [kJ·mol^{-1}] is the reaction enthalpy, n [-] is the hydration state of the highest hydrate, m [-] is the hydration state of the product of the reaction (m < n), M_n [kg·mol^{-1}] is the molar mass of the highest hydrate, $\rho_{min.mat}$ is the minimum density, Δx [-] is reaction conversion, and r [-] is the mass mixing ratio defined as the ratio between the mass of the highest hydrate (m_n) and the mass of the material (m_{mat}), as shown in Eq. 5:

$$r = \frac{m_{\mathrm{n}}}{m_{\mathrm{mat}}} \qquad \text{Eq. 5}$$

At system level, the thermal energy density (ED_{sys}) is defined as the ratio between the amount of thermal energy storage capacity (ESC_{sys}) and the system volume (V_{sys}), as shown in Eq. 6:

$$ED_{sys} = \frac{ESC_{sys}}{V_{sys}} \qquad \text{Eq. 6}$$

The energy storage capacity estimates the total amount of thermal energy that a system can store at nominal conditions and takes into account both the storage capacity of the material and the sensible heat that can be stored in the components that are in contact with the TES material. Therefore, energy storage capacity is calculated according to Eq. 7:

$$ESC_{sys} = ESC_{mat} + ESC_{comp} \qquad \text{Eq. 7}$$

where the thermal energy storage capacity of the material (ESC_{mat}) is calculated as shown in Eq. 8, and the thermal energy storage capacity of all system components (ESC_{comp}) is calculated as shown in Eq. 9:

$$ESC_{mat} = ED_{mat} \cdot \frac{m_{mat}}{\rho_{min}} \qquad \text{Eq. 8}$$

$$ESC_{comp} = \sum_1^x (c_{p.comp.x} \cdot m_{comp.x}) \cdot \Delta T_{op} \qquad \text{Eq. 9}$$

A guideline was developed for determining which components must be taken into account in the calculation, which is presented below:

- There is no contribution of the components for a TES technology based on chemical and sorption reactions in which the reaction pair is stored at ambient temperature.
- In all other cases:
    - If the storage material is moved from one vessel to another during the charge/discharge, the components do not contribute to the thermal energy storage capacity of the system.
    - If the material is always kept in the same vessel, only the components that are totally or partially in contact with or completely surrounded by the material (i.e. pumps, sensors, heaters, …) should be considered.
        - For components that are partially in contact with the material, only the mass of the parts completely immersed in the material are taken into account.
        - The vessel is not taken into account in the calculation because the material does not exchange energy with the vessel.

It is assumed that all the components contributing to ESC_{sys} have the same temperature as the TES material. Thus the thermal energy storage capacity of the components (ESC_{comp}) is measured according to the operation temperature range (ΔT_{op}).

In the case that a component is made of elements of different nature, the calculation of its specific heat ($c_{p.comp.x}$) is performed as follows:

- In case that the specific heat and mass of the different elements of the component are known, the $c_{p.comp,x}$ is calculated as the weighted average.
- In case that the specific heat and mass of the different elements of the component are not known, the c_p of the most representative part is taken as the $c_{p.comp,x}$.

The V_{sys} in Eq. 6 represents de total volume occupied by the system, measured in terms of physical volume of its parts, and is calculated by taking into account the volume enclosed by the shape of the outer surface of the sub-systems, including the insulation. The system is assumed to be a completely compact solid, where cavities are disregarded. Thus, not all components contribute to the V_{sys}, as some might be placed inside other components.

More details on the proposed methodology for evaluating the energy density as performance indicator for TES systems along with its application to three real case studies covering the three different TES technologies can be found in the paper by Romaní et al. [5].

5.2 Seasonal Energy Performance

The performance of the heating and cooling system can be evaluated at all hierarchical levels (i.e. components, sub-systems and system). In the following, we describe the energy indicators that will be used in simulations and demo site evaluation. All the indicators defined in this section are calculated over season or year.

At **component/module level (L1)** the boundaries for the assessment of the energy fluxes are set just around the unit, meaning that we consider the energy delivered by the device over the energy used to run it. Auxiliaries like pumps and thermal losses of the connections are here not considered. Differently from the nominal values defined by the manufacturer, the indicator that will be used is a seasonal figure, meaning that performance refers to a season or year.

The two indicators (*SCOP* and *SEER*) referred to the performance of a device are therefore defined as follows:

$$SCOP_{SH} = {Q_{SH}}/{E_{SH}}$$
$$SCOP_{DHW} = {Q_{DHW}}/{E_{DHW}}$$
$$SEER_{SC} = {Q_{SC}}/{E_{SC}}$$

Eq. 10

Where Q_{SH} is the produced thermal energy for space heating, Q_{DHW} is the yearly produced energy for covering the DHW needs and Q_{SC} is the seasonal thermal energy produced for covering the cooling loads. The energy E refers to the electricity or thermal energy (in the case of the adsorption module) used for producing the useful energy. E_{SH} refers to the consumed energy for covering the space heating load, E_{DHW} is the energy used for the DHW consumption and E_{SC} is the energy consumed for the cooling loads.

These quantities are evaluated under dynamic conditions through simulations, successively calibrated with measured data during lab test and finally used as benchmark in the demo cases.

In the project, these indicators are used to demonstrate the improvement of the components performance with respect to a similar product present in the market.

Apart of the single components, the project studies the combination of more than one device whose interaction improves the performance of the single one studied alone. In the following, we define an indicator that represents a sort of efficiency of the whole **sub-system (L2)**. Conceptually, it is the same as the one used for the component level, but the boundaries change.

For the case of the sub-system, we define the *SPF Seasonal Performance Factor* [kWh/kWh] over the year and obtained as the ratio of the delivered energy from the sub-system over the energy used to produce it.

For the Mediterranean case, the Total delivered energy consists of the cooling energy exiting the latent thermal storage or directly the chiller, and the heat provided for the DHW load. The Total consumed electricity is the electricity used for running the adsorption module, the dry cooler, the chiller, and all the auxiliaries.

In the case of thermal energy used for producing cooling or heating, a comparable indicator is calculated, the SPF_{th} where the *Total consumed thermal energy* is the energy used for producing the delivered energy by a thermal source.

In the Continental case, the *Total delivered energy* includes heating provided by the heat pump or latent thermal storage for space heating and DHW uses, and cooling produced by the heat pump for the cooling load. For the sake of clarity, the SPF can be evaluated for each use: space heating (SH), space cooling (SC) and DHW:

$$SPF_{SH} = \frac{Delivered\ energy\ for\ SH}{Consumed\ electricity\ for\ SH}$$

$$SPF_{DHW} = \frac{Delivered\ energy\ for\ DHW}{Consumed\ electricity\ for\ DHW}$$

Eq. 11

$$\mathrm{SPF}_{SC} = \frac{Delivered\ energy\ for\ SC}{Consumed\ electricity\ for\ SC}$$

In the project, this indicator is very useful for establishing if the integration of different components effectively increases the overall performance with respect a market-available product.

In order to evaluate the performance of the **whole system (L3)**, including renewable energy generation, thermal losses of the distribution system and storages, auxiliaries, distribution terminals in the building and heat exchange with the thermal sources (district heating or solar thermal collectors). Similarly, to the previous case, the SPF_{el} is the ratio between the useful energy required by the users for space heating, cooling and DHW, over the overall energy consumed for delivering it.

$$SPF_{el} = \frac{Total\ delivered\ energy}{Total\ consumed\ electricity}$$

Eq. 12

$$SPF_{th} = \frac{Total\ delivered\ energy}{Total\ consumed\ thermal\ energy}$$

Looking at the whole system, building and user included, this indicator gives and estimation of the real energy system behavior. Compared with a "reference" case where a common reversible heat pump coupled with a centralized thermal storage is used, the SPF for the studied cases should be higher.

5.3 Renewable energy Indicators

5.3.1 Share of Renewable

One of the main goals of the HYBULID project is to optimize the use of thermal and electric storage to maximize the exploitation of renewable energy sources (i.e. solar thermal collectors and PV). Combining thermal and electric storages in a single sub-system, the solar energy can be store in the sorption storage, in the Mediterranean concept, and in electric storage, in both Mediterranean and Continental concept.

According to the energy typology there are different definition of *share of renewable indicators [%]* as reported in [10]. Since, HYBUILD project is focused at building system level, the most common definition is given by the ratio between the energy demand cover by RES ($E_{RES(el,th)}$) over the total energy demand $E_{D(el,th)}$:

$$Share\ of\ renewable_{(el,th)} = \frac{E_{RES*(el,th)}}{E_{D(el,th)}} \cdot 100$$ **Eq. 13**

where *el* and *th* are referred to the electric or thermal generation or demand. It is important to consider that in order to not underestimate the share of renewable the $E_{RES*(el,th)}$ should consist of three attributes, which are:

- $E_{RES-onsite\ (el,th)}$: direct energy used to cover the demand (either electrical or thermal) over a time interval;
- $E_{RES\ -\ stored\ (el,th)}$: the renewable energy coming from electric or thermal storage and used to cover the demand in the considered time interval;
- $E_{RES\ -\ gridFactor\ (el,th)}$: quantity of the energy coming from the grid is given by RES.

This last attribute considers the energy mix from the electricity grid or DH due to renewable energy. This factor changes substantially from one European country to another and it should be considered different at least for the three demo-cases.

5.3.2 Self-consumption

Other relevant KPIs to evaluate the exploitation of renewable through direct use or stored energy are the *self-consumption* and *self-sufficiency* (both evaluated in [%]) which are defined for both electric and thermal production and demand.

The electrical or thermal self-consumption can be expressed as:

$$self - consumption\ (SC_{el,th}) = \frac{E_{RES(el,th)}}{E_{RES-TOT(el.th)}} \cdot 100 \qquad \text{Eq. 14}$$

where $E_{RES(el,th)}$ considered only the energy from renewable directly consumed or the stored into the storage and $E_{RES-TOT(el.th)}$ is the total amount of the energy produced by PV or solar thermal collector.

Conversely, the electrical and thermal self-sufficiency is given by:

$$self - sufficiency\ (SS_{el,th}) = \frac{E_{RES(el,th)}}{E_{D(el,th)}} \cdot 100 \qquad \text{Eq. 15}$$

The difference between the $SS_{el,th}$ and the share of renewable is that in $E_{RES(el,th)}$ only the energy produced and consumed on-site or exchanged with the storage is considered. The grid energy mix related to the primary energy is not taken into account.

When we refers to PV system, the self-consumption and self-sufficiency are affected by different factors such as [14]:

Relative size of PV power and power demand: when PV production is higher than demand the SC is lower while the SP is higher. Conversely, if electricity demand is greater than PV production there is SC>SP. Assuming the PV yield normalized with the building total demand on x axis, the qualitative behaviour of SC and SP is shown in Figure 5, where the cross point represents the NZEB requirement.

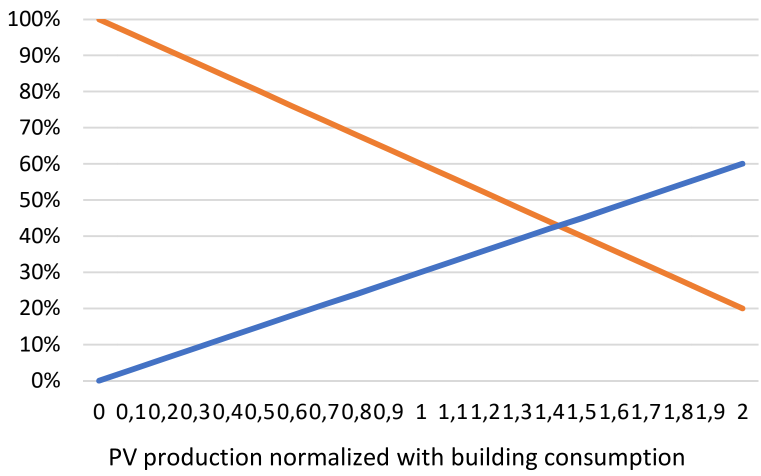


Figure 5 – Qualitative behaviour of SC (in orange) and SS (in blue) over normalized PV production [14].

- *Time resolution*: usually at building level several simulations or monitored data are considered with low resolution time (e.g. hour, 15 minutes) since the dynamic of the building is slow. However, considering for example to compute self-consumption and self-sufficiency starting from hourly data this can lead to an overestimation because the hourly time-step does not consider the rapid dynamic of PV system. For this reason, it is important to choose the proper data time acquisition in the monitoring system according to the specific application.

- *Number of buildings* considered in case that the evaluation is not for only one building.

5.4 Energy savings and CO_2 emission reduction

5.4.1 Energy savings definition

The calculation of the energy savings is essential for the assessment of the performance and of the effectiveness of the HYBUILD solutions since most of the other KPIs derives from this indicator.

The energy savings indicator is calculated, in terms of Primary energy ([%]) as presented in the following equation:

$$PEsav_t = \frac{PE_{hy} - PE_r}{PE_r} \quad \text{Eq. 16}$$

Where

$PE_{hy}\left[\frac{kWh}{year}\right]$ is the total primary energy consumed after HYBUILD implementation.

$PE_r\left[\frac{kWh}{year}\right]$ is the total primary energy consumed in the reference case without the HYBUILD solution.

The energy reduction expected thanks to the HYBUILD solution ranges from 20% to 40 % depending on the configuration and context of application.

In order to calculate the emissions reduction, it is important also to define final energy savings for each energy carrier, described in the following equation:

$$FEsav_{ec} = FE_{hy,ec} - FE_{r,ec} \quad \text{Eq. 17}$$

Where $FE_{hy,ec}$ is the final energy consumption of the energy carrier (ec) after the HYBUILD solution implementation.

$FE_{r,ec}$ is the final energy consumption of the energy carrier (ec) in the reference case without the HYBUILD solution.

$FEsav_{ec}$ is the total annual contribution of the HYBUILD project to the reduction of energy use.

5.4.2 CO_2 emission reduction

Another critical savings potential comes from reductions in operational CO_2 emissions as a result of the solution. Calculating this value could also be helpful in identifying any potential market surrounding renewable energy credits as well. This is typically done by the following formula:

$$CO2sav_t = \sum_{ec} FEsav_{ec} * CO2emf_{ec} \quad \text{Eq. 18}$$

In this case the CO_2 emission savings are calculated by multiplying, for each energy carrier, the CO_2 emission factor per the savings obtained in terms of final energy. The end result is the annual contribution of the HYBUILD project to the reduction of CO_2 emissions.

When referring to the electrical energy, a more accurate estimation of total CO_2 emissions can be performed by adjusting the carbon intensity to consider the specific dispatchable load curve for energy at the location where HYBUILD will be installed. However, using the energy mix carbon intensity generally provides a more conservative estimate and is more generally applicable to different regions.

CO_2 emissions savings of between 10-20% are expected as a result of an optimized BMS, with 20-40% savings for the overall solution depending on the configuration and contexts of the solution.

In order to estimate the total CO_2 emissions savings over the project life, it is important to consider the life expectancy of the solution as a whole. In addition, such an analysis should consider the life-cycle emissions of the solution. Each of these considerations should be aligned with the research and assumptions performed in work package 5.

5.5 Compactness

At the level of the component, the compactness is defined as the ratio of the volume occupied on a functional unit. The volume occupied is defined as the volume of a virtual parallelepipedal shape into which the component can be placed. The choice of a parallelepipedal shape is necessary because it is the easier shape for integration into a building (along walls, on the floor, in a corner…).

Moreover, it has to integrate everything that can be beyond the main box like sensors, screen, control buttons, additional valves, hydraulic or electric connectors but also all the volumes specified in the installation guidelines needed for a good working, for security or for maintenance.

For instance, some air heaters need to be placed at least at 20cm from the wall for ensuring good air ventilation. Gas boilers need to be installed with enough space for ensuring the maintenance of the burner when needed. These additional volumes have to be taken into account.

The functional unit is dependent on the component. For component that produces or emits energy like heat pumps, boilers, heat emitters the functional unit will be the power in kW. For storage components such as electric batteries, PCM storage, water tank, the functional unit will be the energy capacity in kWh.

Example of an outside heat pump unit:

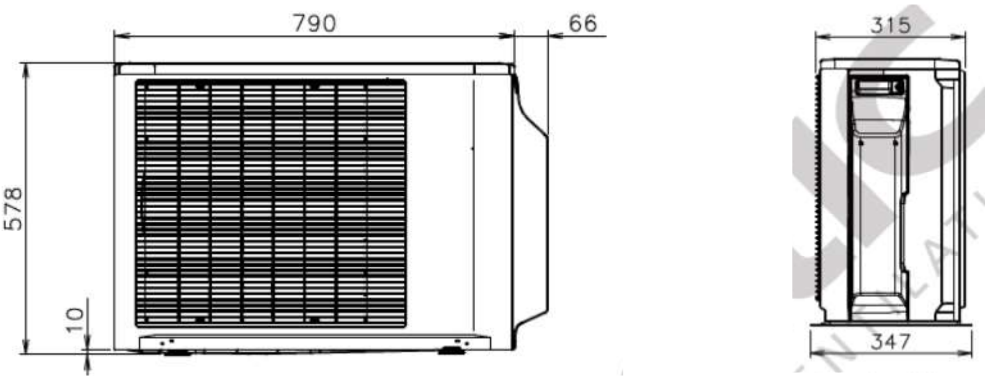


Figure 2: Unit size : 347 x 856 x 578

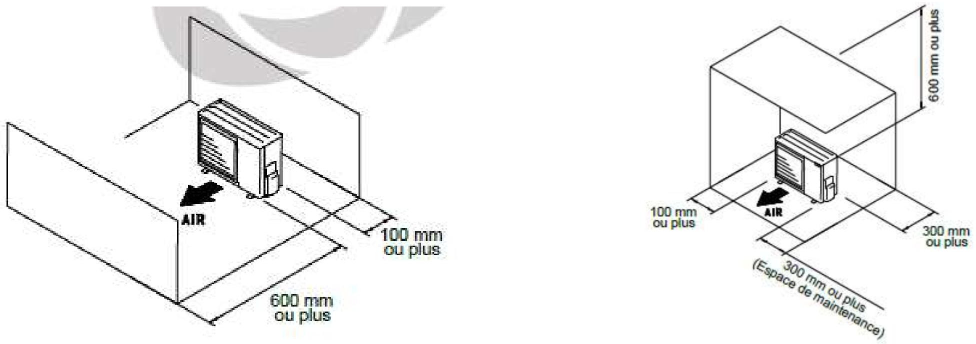


Figure 3 : Volume occupied as defined for compactness calculation: 1047 x 1256 x 1178

At the building level, the compactness is defined as the total volume occupied by the association of every sub-system on a functional unit that represents the provided service.

Thus, the total volume is the sum of volumes occupied by different sub-system. Additional hydraulic components as pumps, valves, filters, air eliminators and expansion vessels have to be considered as sub-systems. However, hydraulic piping or electric wiring won't be considered as a sub-system as it strongly depends on the building configuration and installation realisation.

The HYBUILD system is designed and sized to provide heating, cooling and DHW into buildings. So, we propose here to define the functional unit as the sum of energy provided for a full year. This should be evaluated from the same building energy simulations that will be provided for the system sizing. The sum of energy provided is in fact the aggregation of load profiles for heating, cooling and DHW.

This method allows to have one easy to use indicator but it should be used only to compared systems that provides the same level of services with heating, cooling and DHW.

$$\frac{V_{HP} + V_{PCM\ sto} + V_{W\ sto} + \cdots}{E_{Heat} + E_{Cool} + E_{DHW}} \quad \text{Eq. 19}$$

V_{HP} is the volume occupied by the heat pump

$V_{PCM\ sto}$ is the volume occupied by the pcm storage unit

$V_{W\ sto}$ is the volume occupied by the water storage unit

E_{Heat} is the yearly heating energy needed in kWh/year

E_{Cool} is the yearly cooling energy needed in kWh/year

E_{DHW} is the yearly energy needed for DHW production in kWh/year

It is already mentioned that the compactness of the proposed system is one of the objective of the project and in particular the aim will be to compare the volume of similar components/modules but also sub-systems already present in the market able to have the same performance with the HYBUILD solutions.

It is relevant also to mention that in the case of sub-system level, the compactness can be also expressed as the number of components used and their respective volume.

5.6 Flexibility

Another relevant characteristic of the HYBUILD overall building system is the flexibility provided by the high-level control (or BEMS). This aspect can be addressed from the point of view of the service provided by the smart building under management: on the one hand, the difference between a desired energy behaviour and the results of the optimisation can be an index of how the smart building is able to adapt its consumption to an external request from any smart grid entity or authority (DSOs, energy retailers, aggregators, etc.); on the other hand, the difference between the typical energy behaviour of the managed smart building and the behaviour resulting from the application of the optimisation processes can be used as an index of how much flexible the system is by itself. The two indicators work very well together, as will be shown later in this section.

Relying on the first point of view, a first KPI can be shaped in order to measure how the controlled system adapts its energy behaviour to a desired one. The energy behaviour is represented by the energy consumption profiles of the building, requested and actually performed. The optimisation process that stays behind the control criteria aims at minimising the distance between these two energy profiles, assuming that an external entity, such as a grid operator, has requested a desired energy behaviour, as part of a DR (Demand Response) program the building is participating to. The proposed KPI is a normalised numeric index named Demand Response Power Tracking (DRPT) and is related to the degree of adaptability of the system to this request:

$$DRPT = 1 - \frac{\sum_{i=1}^{n} \left| E_{Response,i} - K_{CL} E_{Demand,i} \right|}{\sum_{i=1}^{n} E_{Response,i}} \qquad \textbf{Eq. 20}$$

$$K_{CL} = \frac{\sum_{i=1}^{n} E_{Response,i}}{\sum_{i=1}^{n} E_{Demand,i}}$$

where:

- n is the number of timestamps of the interested time horizon;
- $E_{Response,i}$ is the energy behaviour of the controlled system in that i^{th} timestamp;
- $E_{Demand,i}$ is the desired energy behaviour request in that i^{th} timestamp;
- K_{CL} is the indicator of the contribution level the building may provide, calculated as normalisation factor to compare the two profiles.

Both the two curves for the demand and the response are considered always positive (i.e., only energy consumption is assumed as requested and performed). The role of K_{CL} is to mathematically make the areas, i.e., the total energy, of the two curves equal. In other words, the profile requested by the external actor, entity or authority is normalised and levelled to the actual consumption of the single building. In other words, the request of the external actor may be also very different from the real capacity of the building: this indicator will represent the ability of the building to follow the consumption pattern suggested by the demanded profile, with a contribution to the general request well represented in percentage by K_{CL}. For this reason, K_{CL} can be considered as a performance indicator itself, of the objective capacity of the building to contribute to the original (not normalised) request received.

The $DRPT$ is a percentage that ranges from 0 to 1. A high $DRPT$ indicates that the smart building is able to follow the consumption trend requested (e.g., it absorbs a higher amount of energy from the grid when a higher demand is requested and a lower one when a lower demand is requested). If it equals 1, the controlled system has adapted to the requested desired behaviour without any deviation. A high $DRPT$ with a K_{CL} near to 1 indicates a building able to follow the requested trend and satisfy the total requested demand at all. Any deviation of K_{CL} from 1 indicates the deviation of magnitude of the contribution provided by the building to the external grid entity or authority, since its total consumption is different from the requested one proportionally. Instead, a low $DRPT$ indicates that the controlled smart building cannot change its behaviour very well for that requested profile. Requested profiles are strongly dependant from the location. As an example, the requested profile in a Mediterranean area may be very different from the one a smart building may receive in a Continental one. For this reason, a low $DRPT$ may mean that the smart building under observation is either not flexible by itself, or not well suited for the grid conditions of the area in which it is located. Here, it is where the following indicator can be profitable.

This third and last KPI related to the building flexibility is intended to represent the actual flexibility of the controlled energy system, in relation to its typical energy behaviour. In this case, the results of the optimisation process reporting the flexibility achieved by the controlled system is put in comparison with its energy behaviour if no request from an external actor would have been received and, in any case, no optimisation is performed at all. This difference is a measure of the flexible behaviour of the system in that operation. This KPI is a numeric index named Flexibility Capacity Index (FCI) and is related to the capacity of the system to modify its energy behaviour:

$$FCI = \frac{\sum_{i=1}^{n} \left| E_{typical,i} - E_{optimized,i} \right|}{n \, E_{typical,i}} \qquad \textbf{Eq. 21}$$

where:

- $E_{typical,i}$ is the typical energy behaviour of the system in that i^{th} timestamp.
- $E_{optimized,i}$ is the optimized energy behaviour of the system in that i^{th} timestamp.

The FCI is actually the average percentage of flexibility provided with respect to the typical energy behaviour of the system evaluated over the entire time horizon, made up by n timestamps. A high FCI indicates that the system is intrinsically able to provide a high level of flexibility, with respect to the optimisation performed. So, a high FCI with a low $DRPT$ indicates that the problem is that the smart building is flexible by itself but not well suited for the location in which it receives that requests from the external entity or authority. This solves the doubt left by the analysis of a low $DRPT$ by itself. On the contrary, a high $DRPT$ with a low FCI indicates that the smart building is able to follow the shape of the requested power consumption profile, even if its typical behaviour is already similar to the desired one, even without optimisation.

It is worth noting that the FCI works also in absence of DR programs participation. In fact, it is only dependant to the optimisation performed, which in its turn depends on its objectives. The objectives of the optimisation may be directed to the provision of DR services or not: the smart building may be optimised for example for auto-consumption, efficiency improvement, cost reduction, etc. or even a combination of them, in order to find a trade-off solution. In this case, the FCI still work, since it is an indication of the flexibility of the building by itself, implementing a specific optimisation process.

5.7 Return on investment (ROI)

Return on Investment (or ROI) is a common business tool to prioritize whether one investment is preferable to another investment. This, combined with the expected “payback period” of the investment, can be used to determine if an investment is interesting to a company. ROI is typically calculated through the following formula:

$$ROI = \frac{Gain\ from\ Investment - Investment\ Cost}{Investment\ Cost} \quad \text{Eq. 22}$$

The total investment cost considered in this analysis should include all the cost of all developed sub-systems (C_{eq}). In addition, engineering costs (C_{en}), labor and installation costs (C_l), and financing costs relating to the installation (C_f) should be considered.

The formula for total investment cost is as follows:

$$Investment\ Cost\ (C_o) = \sum C_{eq} + C_{en} + C_l + C_f \quad \text{Eq. 23}$$

The gain from investment should be calculated considering the target market where the system is deployed. This will be explored further in the business models developed in Task 7.4. In any case, the gain from investment should take into account the cost reductions from primary energy savings (CPE_{sav}) due to the different factors (hybrid solutions linked to the renewable system, optimized energy management, etc.) and the possible income coming from demand response participation (DR). It is relevant to highlight that both investment and profit will be different for the Mediterranean or the Continental concept and reasonably it will lead to different results. It should be evaluated over the year with hourly resolution, as often the cost value of primary energy savings may change during the day. The formula for the gain from investment becomes:

$$Gain\ from\ Investment\ (GI) = \sum_{h=1}^{T*8760} (CPE_{sav} + DR) \quad \text{Eq. 25}$$

The cost reduction for primary energy savings (CPE_{sav}) will consider the inputs for total primary energy savings described in Section 5.4.1 within the market context in which the solution is being evaluated. Therefore, a separate function should be defined for this parameter for each specific case (including the specific energy billing structure if possible). Note that the hour where the energy savings occurs should always be considered, even if this differs from the hour when the energy was produced due to the use of storage in the HYBUILD solution.

For the *DR* term, it is important to note that access to the demand response market in Europe is highly regulated, with most markets currently closed to residential participants. However, proposed changes to energy markets in the Clean Energy for All Europeans package could result in many European countries opening up this market either directly or indirectly to residential prosumers. For this reason, the demand response term should only be evaluated "as needed"- only in those cases where a specific monetary value for flexibility can be captured. In these cases, the potential earnings from the local market should be considered.

T refers to the time period evaluated in years; it is multiplied by 8760 since for this equation since the time periods should be evaluated hourly.

In addition to ROI, the Net Present Value (NPV) can be used to estimate the current value of an investment, accounting for inflation and other factors. This is generally a more accurate and informative version of the "payback period" analysis, properly discounting future earnings to account for the real value of money over time. With this analysis, the year in which the NPV equals 0 can be considered the "payback period". The NPV formula is as follows:

$$NPV = \sum_{t=1}^{T} \frac{GI}{(1+r)^t} - C_o \quad \text{Eq. 26}$$

Where C_o is the initial investment cost, t is the current year, T is the total number years considered (can be 25 years or the expected system lifetime of the equipment), and r is the discount rate (which should be based on available investments and/or inflation).

The ambitious target that HYBUILD project will generate is to have a simple payback period of 8 years for building non-connected to DHC and 15 years for building connected to DHC. For this reason, this KPI is applied at the overall building system level.

6 Other relevant PIs

Four additional PIs were also identified in relation to HYBUILD, which are worth mentioning and defining in this deliverable:

- Primary energy savings triggered by the project funded [GWh/year per million €]
- Total additional investments in sustainable energy triggered by the project within its duration [million €]
- Contribution of HYBUILD to the reduction of waste
- Contribution of HYBUILD to the reduction of material resources

The former one is related to one of the PI (Energy savings and CO_2 emission savings), but it also has to take into account other aspects such as the number of buildings and climate conditions of the locations where HYBUILD system will be implemented.

$$PES_{project} = \frac{\sum_i (PE_{hy} - PE_r)_i}{PB} \cdot 1{,}000{,}000\ € \quad \text{Eq. 27}$$

where $PE_{hy,i}$ [GWh/year] is the total primary energy consumed after HYBUILD implementation in building “i”, $PE_{r,i}$ [GWh/year] is the total primary energy consumed in the reference case of building “i", where sub index “i” accounts for each of the buildings where the HYBUILD system will be installed, and PB [million €] is the total project budget.

The second PI accounts for the total amount of money that was invested in sustainable energy during the project duration as a direct consequence of the activities carried out within the framework of the project.

The final two PIs relate to the percent reduction of waste and material resources triggered by the project. While these areas are not a primary focus of the HYBUILD solution, the work performed in other areas (including the focus on compactness in KPI and the LCA in Work Package 5) can directly contribute to potential savings.

7 Conclusions

The present report illustrates the process of definition of the KPIs to be used at different stages of the project to evaluate the impact of the HYBUILD solutions.

As first step, a list of performance indicators has been collected with the help of consortium partners. These performance indicators refer to the different hierarchical levels in which the two HYBUILD concepts are articulated, namely components/modules, hybrid subsystems and overall building system. Since the project involves the development of several technologies with a relevant degree of complexity and multiple aspects have to be considered, it was obtained a quite long and varied list consisting of over 40 performance indicators. For each of them, the following information has been provided:

- Indicator name;
- Definition, with some explanation about how the PI is calculated (with specific reference to the HYBUILD application cases);
- Unit of measurement;
- Application level (i.e. building, sub-system or component/module).

Among the PIs, the most significant have been identified, considering in particular their relevance for the measurement and management of the progress towards project targets, as they are expressed in the DoA and in the call for proposal.

The seven KPIs (Thermal Energy Storage Density, Seasonal Energy Performance, share of renewable and self-consumption, Energy savings and CO_2 emission savings, Compactness, Flexibility and Return on Investment) have been agreed with the consortium and they will be quantified throughout the project and compared with the initial objectives.

In the case of KPI1 - Thermal Energy Storage Density and KPI2 - Seasonal Energy Performance, values obtained within the project will be compared with state of the art ones, thus demonstrating the improvement of the HYBUILD components performance with respect to similar products present in the market. The Seasonal Energy Performance indicator in particular is very useful for demonstrating how the integration of the different components effectively increases the overall systems performance with respect to market-available products.

KPI 3 – Share of renewable and self-consumption will be used to demonstrate how the optimisation of the use of thermal and electric storage enabled by HYBUILD technologies will help to maximize the exploitation of renewable energy sources (i.e. solar thermal collectors and PV).

KPI.4 – Energy savings and CO_2 emission savings will enable the evaluation of the energy savings obtainable with the developed systems, which is essential for the assessment of their performance and effectiveness compared with the expected building energy reduction ranging from 20% to 40% and CO2 emissions reduction of 37.4% at EU building level.

Compactness and easiness of integration, and flexibility in terms of high level controls (BEMS) will be evaluated respectively by means of KPI.5 – Compactness and KPI.6 – Flexibility.

Finally, the profitability of an investment into one of the HYBUILD solutions will be assessed by means of KPI7 – Return on Investment and compared with the expected ROI of 8 years for building non-connected to DHC and 15 years for buildings connected to DHC.
The present report illustrates the process of definition of the KPIs to be used at different stages of the project to evaluate the impact of the HYBUILD solutions.

References

[1] V. Palomba, J. Gasia, J. Romaní, A. Frazzica, and L. F. Cabeza, “Definition of Performance Indicators for Thermal Energy Storage,” in *Recent Advancements in Materials and Systems for Thermal Energy Storage: An Introduction to Experimental Characterization Methods*, A. Frazzica and L. F. Cabeza, Eds. Cham: Springer International Publishing, 2019, pp. 227–242.

[2] “CEN - EN 15341 - Maintenance - Maintenance Key Performance Indicators | Engineering360.” [Online]. Available: https://standards.globalspec.com/std/1012513/cen-en-15341. [Accessed: 15-Nov-2018].

[3] “ECES Annex 30 – Thermal Energy Storage for Cost-Effective Energy Management.” .

[4] L. F. Cabeza, E. Galindo, C. Prieto, C. Barreneche, and A. Inés Fernández, “Key performance indicators in thermal energy storage: Survey and assessment,” *Renew. Energy*, vol. 83, pp. 820–827, 2015.

[5] J. Romani, J. Gasia, H. Sole’, Y. Kato, and L. F. Cabeza, “Evaluation of energy density as performance indicator for thermal energy storage at material and system levels,” *Appl. Energy*, vol. 235, pp. 954–962, 2019.

[6] D. Gibb *et al.*, “Applications of Thermal Energy Storage in the Energy Transition. Benchmarks and developments,” Public Report of the International Energy Agency Annex 30., 2018.

[7] C. Del Pero, N. Aste, H. Paksoy, F. Haghighat, S. Grillo, and F. Leonforte, “Energy storage key performance indicators for building application,” *Sustain. Cities Soc.*, vol. 40, no. September 2017, pp. 54–65, 2018.

[8] R. Fedrizzi *et al.*, “D6.3a Performance of Studied Systemic Renovation Packages – Methods,” 2015.

[9] “UNI EN 14825:2016.” [Online]. Available: http://store.uni.com/catalogo/index.php/uni-en-14825-2016.html?josso_back_to=http://store.uni.com/josso-security-check.php&josso_cmd=login_optional&josso_partnerapp_host=store.uni.com. [Accessed: 08-Nov-2018].

[10] D. Antonucci and W. Pasut, “KPIs for Building [Dataset]. Zenodo.” 2017.

[11] I. Malenković, “Definition of Performance Figures for Solar and Heat Pump Systems,” 5.1.3, May 2012.

[12] A. Zottl, R. Nordman, and M. Miara, “Benchmarking method of seasonal performance D4.4. Benchmarking method of seasonal performance under consideration of boundary conditions.,” SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector SEPEMO-Build, Apr. 2012.

[13] “IEC 61724-1:2017 | IEC Webstore | rural electrification, solar power, solar panel, photovoltaic, PV, smart city, LVDC.” [Online]. Available: https://webstore.iec.ch/publication/33622. [Accessed: 08-Nov-2018].

[14] R. Luthander, J. Widn, D. Nilsson, and J. Palm, “Photovoltaic self-consumption in buildings: A review,” *Appl. Energy*, vol. 142, pp. 80–94, 2015.

[15] Eurostat, “Calculation methodologies for the share of renewables in energy consumption - Statistics Explained.” [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Calculation_methodologies_for_the_share_of_renewables_in_ener

gy_consumption#Definition_of_the_primary_energy_content_of_fuels. [Accessed: 08-Nov-2018].

[16] Eurostat, "Greenhouse gas emission statistics - emission inventories - Statistics Explained," 2017. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics. [Accessed: 03-Oct-2018].

[17] EEA European Environment Agency, *Nitrogen oxides (NOx) emissions — European Environment Agency*. 2018.

[18] EPA United States Environmental Protection Agency, "Sulfur Dioxide Basics," 2018.

[19] World Health Organization, "for Health," *World Health*, vol. 19, no. 3, p. 237, 2006.

[20] European Enviromental Agency, *Air quality in Europe — 2015 report*. 2015.

[21] "Handbook." [Online]. Available: https://www.ashrae.org/technical-resources/ashrae-handbook. [Accessed: 15-Nov-2018].

[22] P. A. J. Donkers, L. C. Sögütoglu, H. P. Huinink, H. R. Fischer, and O. C. G. Adan, "A review of salt hydrates for seasonal heat storage in domestic applications," *Appl. Energy*, vol. 199, pp. 45–68, 2017.