BIOBUILD

Thermal Solutions for Green Buildings

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Deliverable 1.3

Definition and selection of KPIs

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History of changes in the Deliverable D1.3 Definition and selection of KPIs

Date of change	Section/Page	Nature of change and reason
27/10/25	Section 2.1, page 6	**Reviewer's comment 1:** Add the used criteria into the methodological section (2.1). **Reply:** The used criteria were added in Section 2.1 in the revised Deliverable.
27/10/25	Section2.1, page 6	**Reviewer's comment 2:** Make a link with D1.2 and discuss the compatibility of the PIs from the viewpoint of current hENs and possible needs. **Reply:** Discussion on the KPIs and Deliverable D1.2 is added.
27/10/25	Table 3, page 19	**Reviewer's comment 3:** Add the relevant European Standards (such as EN 15804 and 15978) prepared by CEN TC 350) as references and corresponding relevant indicators. **Reply:** A new column with European/international standards to which KPIs are related was added to Table 3.
27/10/25	Section 2.1, page 6	**Reviewer's comment 4:** Make link to D2.1, D2.2 and other coming relevant documents that test the developed products. Make conclusions and recommendations which of the selected PIs are relevant for assessing of results. **Reply:** Discussion on the link between D2.1, D2.2 and other relevant WPs is addressed.
27/10/25	Section 3, Table 1, page 19	**Reviewer's comment 5:** Consider using the term Product instead of Material in Table 3. **Reply:** The term Material is changed to Product in Table 3.

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1 Introduction

This deliverable “Definition and selection of KPIs” is part of the ongoing work within the project BIOBUILD in the framework of WP1” Specific climate considerations and building typological classification”. The main aim of BIOBUILD is to accelerate the transition towards a circular and low-carbon construction sector by developing and deploying innovative, bio-based building components and solutions.

Performance indicators (PIs) are fundamental to allow the comparison of different technologies solutions that can be used for building applications and evaluate the potential benefits in different aspects. This document collects a number of performance indicators that can be suitable for application from material to system level to quantitatively analyse various aspects of novel materials developed for building applications.

The methodological approach followed should lead to the selection of the "key" ones that should be included in the project BIOBUILD. The first step of the KPIs identification was a deep literature review of the performance indicators (PIs) used to evaluate the performance of building components in different aspects. The selection of relevant parameters (KPIs) was then done considering the stakeholder perspective regarding the main objectives of the project. The set of PIs presented in this deliverable represents a proposal of reference parameters intended to guide and support the monitoring of progress across all work packages, ensuring alignment with project objectives. For instance, the development of materials, the demo testing campaigns, building simulations, and environmental evaluation will rely on the PIs and KPIs defined as a basis for performance assessment.

The different PI and KPIs will ensure the target of technical, environmental, and economic specifications in the project BIOBUILID.

This report is structured as follows: Section 2 reports the list of the performance indicators selected with methodology used. The results of the PIs evaluations and the listed KPIs are reported in Section 3. Conclusions of this report are in Section 4.

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2 List of performance indicators

2.1 Methodology of PI selection

The selection of proper KPIs is fundamental to allow the comparison of the BIOBUILD technology with similar solutions that are being developed or already commercially available.
In order to be relevant and avoid confusion amongst them, these parameters should be simple, with a unique definition and meaningful. Generally, there is no clear agreement of what KPIs should be selected, Moreover, in the literature, a large number of performance indicators can be found which can make their selection a complicated task.

The link between Deliverable D1.2 "Technical, market codes, and certification strategies" and the KPIs in D1.3 is in the specification, evaluation, and alignment with current harmonized European standards (hENs) and the market's certification requirements for thermal energy storage, safety, durability, and environmental performance.

Performance indicators currently referenced in hENs or related European Assessment Documents (EADs) for building materials (including integrated PCMs) cover the thermal performance of the material, e.g., measurement of latent heat capacity, thermal conductivity and phase transition temperature range related to specific climatic and operational needs. Examples are the standards EN 12 664, EN 12667 and EN 13950 that are compatible but not updated for the needs of the project where solid wood and wood particles are involved. Leaching and cycling stability are examples of properties that are not fully covered by hENs and need better protocols.
Considering the mechanical integrity (e.g., the standards EN 13950, EN 998-1), hENs are focused on traditional building materials (gips, mortar, other structural materials) while no hENs were found on the strength and dimensional stability of bio-composites with PCM.
In contrast, the fire safety (reaction to fire) of materials covers the categories of construction products, floorings and thermal insulation products (EN 13501-1) where the indicators for fire reaction, emissions, and leaching must be met for a specific product family.
It is concluded that compatibility depends on how PIs are selected for testing and whether the bio-composites with bioPCM fit within the scope of current hENs. Novel biobased materials with bioPCM require custom-made methods to a specific order, designed and built according to the unique specification assessment methods or additional performance indicators beyond standard frameworks.

While hENs cover conventional building materials, there are some standardization gaps for novel biomaterials with added functionality, e.g., long-term stability under diverse climatic scenarios, leakage, compatibility with the existing composites in use and a need for standardization of assessment protocols for new PCM types or adaptive, smart building envelopes. Additional hENs or EADs may be required for market acceptance and certification, particularly as bioPCMs are diverse as composition and function.

The objective of Deliverable 2.1 was the selection between thermal or microwave pre-treatment of solid wood, fibres and particles to optimise the uptake of phase change material (PCM) and reduce its leaching, while Deliverable 2.2 had the specific objective to upscale the technology for impregnation of bioPCM into solid wood and wood fibres/particles and optimization of the bioPCM retention. Thus, only leaching of bioPCM appears to be a PI at material level and it was listed as such (Section 2.2). There are no hENs or even other standards for determination of PCM leaching, which confirms the need of custom-made designed method beyond standard testing frameworks.

In this work, a simplified approach for the KPIs definition was used. A literature survey of performance indicators was done in the existing literatures, legislations, and other European projects. Finally, the most relevant PIs, which are relevant for the project and for building applications, were selected with the support of the partners involved in the project. The selection was based on a set of predefined criteria, including clarity and ease of interpretation, measurability using available data and tools, relevance to the project objectives, and potential for benchmarking across different technologies.

Indicators that were complex, lacked standard definitions, or were not directly applicable to BIOBUILD. This ensured that the chosen PIs are both practical and impactful for performance evaluation.

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In this document PIs were divided in several categories:

- Performance indicators at material level.
- Performance indicators at building/system level.
- Economic performance indicators.
- Environmental performance indicators.
- Architectural indicators.
- Other performance indicators.

The following section will report a detailed description of all PIs identified to select the key ones in the next step.

2.2 Performance indicators at material level

Energy storage capacity	
Description	Maximum amount of energy that can be stored in the storage within a pre-defined temperature range
Units	[kWh] or [kJ]
References	Del Pero, C., Aste, N., Paksoy, H., Haghighat, F., Grillo, S., Leonforte, F. Energy storage key performance indicators for building application. Sustainable Cities and Society 40 (2018) 54–65

Energy density	
Description	Energy stored in one m^3 or kg of storage material
Units	[kJ/m^3] or [kJ/kg]
References	Romaní, J., Gasia, J., Solé, A., Takasu, H., Kato, Y., Cabeza, L.F. Evaluation of energy density as performance indicator for thermal energy storage at material and system levels. Applied Energy 235 (2019) 954-962

Latent heat of fusion	
Description	Amount of energy that must be supplied to convert one mole of solid into liquid
Units	[kJ/kg]
References	R. A. Kishore, M. V. A. Bianchi, C. Booten, J. Vidal, and R. Jackson, Parametric and sensitivity analysis of a PCM-integrated wall for optimal thermal load modulation in lightweight buildings. Applied Thermal Engineering 187 (2021) 116568

Specific heat capacity	
Description	Amount of heat to be supplied to 1 kg of a material to produce a unit change in its temperature
Units	[J/kg·K]
References	Romaní, J., Gasia, J., Solé, A., Takasu, H., Kato, Y., Cabeza, L.F. Evaluation of energy density as performance indicator for thermal energy storage at material and system levels. Applied Energy 235 (2019) 954-962 EN ISO 52000-1, Energy Performance of Buildings. Overarching EPB Assessment. Part 1: General Framework and Procedures, 2017. ASTM E1269-11(2018) Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry

Density	
Description	The mass of a unit volume of a material substance
Units	[kg/m^3]

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References	D. A. El-Raheim, A. Mohamed, H. Abou-Ziyan, and M. Fatouh. The essential properties governing the appropriate selection of phase change materials integrated into heavy structure buildings. Energy 266 (2023) 126515

Thermal conductivity	
Description	Refers to the intrinsic ability of a material to transfer or conduct heat
Units	[W/m·K]
References	D. A. El-Raheim, A. Mohamed, H. Abou-Ziyan, and M. Fatouh. The essential properties governing the appropriate selection of phase change materials integrated into heavy structure buildings. Energy 266 (2023) 126515 R. A. Kishore, M. V. A. Bianchi, C. Booten, J. Vidal, and R. Jackson, Parametric and sensitivity analysis of a PCM-integrated wall for optimal thermal load modulation in lightweight buildings. Applied Thermal Engineering 187 (2021) 116568

Temperature coefficient for thermal conductivity (optional, if conductivity is not constant)	
Description	This is the thermal conductivity change per unit temperature excursion from 20 °C. If the thermal conductivity is constant this coefficient equals 0
Units	[W/m·K^2]
References	EnergyPlus^{TM} Input Output Reference, 2021.

Thermal effusivity	
Description	A measure of an object's ability to exchange thermal energy with its surroundings. A high value for thermal effusivity corresponds to a material that can easily absorb and release heat to the surface. $$b = \sqrt{\lambda \cdot \rho \cdot c}$$ Where λ is the thermal conductivity, ρ is the density and c is the specific heat capacity
Units	[W/m^2·K]
References	Lopez-Arias, V. Francioso, M. Velay-Lizancos, High thermal inertia mortars: New method to incorporate phase change materials (PCMs) while enhancing strength and thermal design models, Construction and Building Materials 370 (2023) 130621

Packing factor	
Description	$PF = \frac{V_{TES\ material}}{V_{TES\ system}}$ where $V_{TES\ material}$ is the actual volume of TES material in the TES system m^3/L and $V_{TES\ system}$ is the maximum volume of TES material that the TES system can contain m^3/L
Units	[-]
References	Cabeza, L.F., Galindo, E., Prieto, C., Barreneche, C., Fernández, A.I. Key performance indicators in thermal energy storage: Survey and assessment. Renewable Energy 83 (2015) 820-827

Operating temperature	
Description	Range of operating temperature of the thermal energy storage
Units	[ºC]
References	Palomba, V., Frazzica, A. Comparative analysis of thermal energy storage technologies through the definition of suitable key performance indicators. Energy and Buildings 185 (2019) 88-102

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	Romaní, J., Gasia, J., Solé, A., Takasu, H., Kato, Y., Cabeza, L.F. Evaluation of energy density as performance indicator for thermal energy storage at material and system levels. Applied Energy 235 (2019) 954-962

PCM melting temperature	
Description	The temperature at which the substance goes from a solid to a liquid
Units	[°C]
References	Dong, Y., Zhang, L., Wang, P., Liu, Z., Su, X., Liao, H., & Jiang, X. Potential evaluation of energy flexibility and energy-saving of PCM-integrated office building walls. Journal of Building Engineering 79 (2023) 107857

PCM hysteresis temperature difference	
Description	High and low temperature difference of freezing/melting curve. This input object in EnergyPlus adds a hysteresis effect that allows the melting/freezing process to follow different curves, representing an effect often seen in actual applications of PCM in buildings
Units	[Δ °C]
References	K. Biswas, Y. Shukla, A. Desjarlais, and R. Rawal. Thermal characterization of full-scale PCM products and numerical simulations, including hysteresis, to evaluate energy impacts in an envelope application. Applied Thermal Engineering 138 (2018) 501-512

Durability (life cycle or design lifetime)	
Description	The lifetime of a storage may be specified in several different ways depending on the application and hence on which mechanism is most significant. For applications in which the storage is regularly charged and discharged, the most appropriate measure of lifetime is the number of charge/discharge cycles over which the storage maintains the storage nominal capacity. Therefore, for thermal storage systems, lifetime just depends on mechanical resistance of the materials and subcomponents lifetime used in the construction and operation of the storage system because nominal storage capacity is just minimally affected by the medium degradation rate. It can be referred to the assumed maximum number of cycles during which the storage system can release at least 80% of the designed useful capacity.
Units	[cycle]
References	Del Pero, C., Aste, N., Paksoy, H., Haghighat, F., Grillo, S., Leonforte, F. Energy storage key performance indicators for building application. Sustainable Cities and Society 40 (2018) 54-65 ISO 13823:2008 General principles on the design of structures for durability

Degradation	
Description	Degradation of performance of the storage medium over 1000 cycles
Units	[%/1000 cycles]
References	Hoivik, N., Greiner, C., Barragan, J., Iniesta, A. C., Skeie, G., Bergan, P., Blanco-Rodriguez, P., Calvet, N. Long-term performance results of concrete-based modular thermal energy storage system. Journal of Energy Storage 24 (2019) 100735

Technology Readiness Level (TRL)	
Description	The technology readiness level (TRL) indicates the maturity of a given technology. The TRL spans over nine levels
Units	Number from 1 to 9
References	Cabeza, L.F., Galindo, E., Prieto, C., Barreneche, C., Fernández, A.I. Key performance indicators in thermal energy storage: Survey and assessment. Renewable Energy 83 (2015) 820-827

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Cost	
Description	Market price of the storage material
Units	[€/
References	Cabeza, L.F., Galindo, E., Prieto, C., Barreneche, C., Fernández, A.I. Key performance indicators in thermal energy storage: Survey and assessment. Renewable Energy 83 (2015) 820-827

Availability	
Description	Ease to purchase the storage material
Units	Descriptive
References	Fernández, A.I., Martínez, M., Segarra, M., Martorell, I., Cabeza, L.F. Selection of materials with potential in sensible thermal energy storage. Solar Energy Materials and Solar Cells 94 (2010) 1723-1729

Recyclability	
Description	Possibility to reuse the storage material after the end of life
Units	Yes/No
References	Tatsidjodoung, P., Le Pierrès, N., Luo, L. A review of potential materials for thermal energy storage in building applications. Renewable and Sustainable Energy Reviews 18 (2013) 327-349

Safety aspects	
Description	Aspects to be considered to avoid safety risks associated to the use of the storage material
Units	Descriptive
References	Gil, A., Medrano, M., Martorell, I., Lázaro, A., Dolado, P., Zalba, B., Cabeza, L.F. State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization. Renewable and sustainable energy reviews 14 (2010) 31-55

Leachability of phase change material (PCM)	
Description	Ability of PCM to leach from its containment material over time.
Units	[g/m^2/time]; [% mass loss/ time]; [% mass loss/number of thermal cycles]
References	Nazari, M., Jebrane, M., Terziev, N., 2022. Solid wood impregnated with a bio-based phase change material for low temperature energy storage in building application. Journal of Thermal Analysis and Calorimetry (2022) 1-16. EN 84; Wood Preservatives – Accelerated Ageing of Treated Wood Prior to Biological Testing – Leaching Procedure. EN 113-2; Durability of Wood and Wood-Based Products – Test Method against Wood Destroying Basidiomycetes – Part 2: Assessment of Inherent or Enhanced Durability.

Susceptibility to bio-deterioration (stain and mould fungi)	
Description	Ability of the biomaterial containing PCM to support growth of stain and mould fungi, providing nutrients and suitable conditions for colonization.
Units	Visual assessment based on % area covered by the fungi
References	American Wood Protection Association Standard E24-06 (2015) Laboratory Method for Evaluating the Resistance of Wood to Stain and Mould Fungi.

2.3 Performance indicators at building/system level

Seasonal coefficient of performance	
Description	$SCOP = {Q_{SH}}/{E_{SH}}$

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	where: Q is the demand of heating (SH) E is the electric energy to cover the demand
Units	[-]
References	Pelella, F., Zsembinszki, G., Viscito, L., Mauro, A. W., Cabeza, L. F. Thermo-economic optimization of a multi-source (air/sun/ground) residential heat pump with a water/PCM thermal storage. Applied Energy 331 (2023) 120398

Demand Factor	
Description	$D_F(t) = \frac{Demand}{Maximum\ possible\ demand}$ 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.
Units	[-]
References	Antonucci, D., Pasut, W. KPIs for Building [Dataset]. Zenodo, 2017

Annual heating and cooling demand per net useful area	
Description	$Q_t = \frac{Q_{th}}{A}$ where Q_{th} is the thermal demand and A is the considered area. It can be evaluated over a month or over a year
Units	$\left[\frac{kWh}{m^2}\right]$
References	Antonucci, D., Pasut, W. KPIs for Building [Dataset]. Zenodo, 2017 ISO 52016-1:2017 Energy performance of buildings – Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads - Part 1: Calculation procedures

Final energy use	
Description	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
Units	[kWh]
References	Fedrizzi, R., Dipasquale, C., Bellini, A., Gustafsson, M., Bales, C., Ochs, F., Dermentzis, G., Nouvel, R., Cotrado, M. D6.3a performance of the studied systemic renovation packages – method, EC FP7 project iNSPiRe, Grant agreement no. 314461 (2016)

Primary energy use	
Description	$PE = FE * PEf_{ec}$ where PEf_{ec} is the Primary Energy Factor, which depends on the calculation method and inclusion or not of renewable
Units	[kWh]
References	Al Dakheel, J., Del Pero, C., Aste, N., & Leonforte, F. (2020). Smart buildings features and key performance indicators: A review. Sustainable Cities and Society, 61, 102328.

Primary energy ratio (PER)	
Description	Defined as the ratio of the useful energy output to primary input. $PER = \frac{useful\ energy}{primary\ energy\ (PE)}$ PER can include or not renewable

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Units	[-]
References	Malenković, I. Definition of Performance Figures for Solar and Heat Pump Systems. Technical Report 5.1.3, May 2012 Zottl, A., Nordman, R., Miara, M. 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

Energy savings	
Description	The energy saving indicator is calculated, in terms of primary energy as presented in the following equation: $PEsav_t = \frac{PE_{hy}-PE_r}{PE_r}$ [%] where: $PE_{hy}\left[\frac{kWh}{year}\right]$ is the total primary energy consumed after BIOBUILD 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 BIOBULD solution implementation, $FE_{r,ec}$ is the final energy consumption of the energy carrier (ec) of the reference case
Units	[-]
References	Castell, A., Martorell, I., Medrano, M., Pérez, G., Cabeza, L. F. Experimental study of using PCM in brick constructive solutions for passive cooling. Energy and buildings 42(4) (2010). 534-540.

Thermal stability	
Description	Thermal stability refers to the ability of the building integrating the BIOBUILD concept to maintain a stable indoor temperature under daily oscillations. $TSC = \frac{\Delta T\ inner\ surface}{\Delta T\ outer\ surface}$
Units	[-]
References	A. Castell, I. Martorell, M. Medrano, G. Pérez, L.F. Cabeza. Experimental study of using PCM in brick constructive solutions for passive cooling. Energy and Buildings (2010) 534-540

Amplitude of temperature swing	
Description	It corresponds to the difference between maximum and minimum temperatures inside the house during daily oscillations
Units	°C
References	A. Castell, I. Martorell, M. Medrano, G. Pérez, L.F. Cabeza. Experimental study of using PCM in brick constructive solutions for passive cooling. Energy and Buildings (2010) 534-540

Thermal lag	
Description	Thermal lag in a building refers to the delay between when the outside temperature changes and when the inside temperature responds. Thermal lag is demonstrated as in the BIOBUILD building the indoor temperature

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	tends to respond more gradually and reduced variations compared to outdoor temperature fluctuations under different daily temperature oscillations.
Units	Hours
References	A. Castell, I. Martorell, M. Medrano, G. Pérez, L.F. Cabeza. Experimental study of using PCM in brick constructive solutions for passive cooling. Energy and Buildings (2010) 534-540

Thermal distribution	
Description	It corresponds to the temperature difference inside the building. During the demo testing indoor temperature of the BIOBUILD house are measured at selected locations to understand the thermal distribution inside and near the building envelopes.
Units	°C
References	A. Castell, I. Martorell, M. Medrano, G. Pérez, L.F. Cabeza. Experimental study of using PCM in brick constructive solutions for passive cooling. Energy and Buildings (2010) 534-540

Heat retention post-set point	
Description	It is the measure of how long the building maintains the setpoint temperature after the heating or cooling system is turned off.
Units	Hours
References	Kalbasi, R., Sedaghat, A., Khanafer, K., Al-Masri, A. An experimental study on application of phase change materials in a portable cabin in Wintertime of Kuwait under Active/Passive cooling. Applied Thermal Engineering 257 (2024) 124429

Global daily energy reduction (GDER)	
Description	$GDER = ED_{reference} - ED_{optimised}$ 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
Units	[kWh]
References	HYBUILD project

2.4 Economic performance indicators

Operational expenditures (OPEX)	
Description	OPEX is the cost of operating an equipped facility and consists of the direct costs (ex. labour, material, repair/maintenance, etc.) as indirect costs such as the tax burden and revenue
Units	[€/year]
References	Palomba, V., Frazzica, A. Comparative analysis of thermal energy storage technologies through the definition of suitable key performance indicators. Energy and Buildings 185 (2019) 88-102
Capital expenditure (CAPEX)	
Description	CAPEX refers to the cost spent to create future profits, which is usually the total investment cost of a project in the plant construction periods and consist of the equipment and installation costs
Units	[€]
References	Palomba, V., Frazzica, A. Comparative analysis of thermal energy storage technologies through the definition of suitable key performance indicators. Energy and Buildings 185 (2019) 88-102

Return on investment (ROI)

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Description	Ratio between the difference between the gain from investment and investment cost and the investment cost. $ROI = \frac{Gain\ from\ Investment - Investment\ Cost}{Investement\ Cost}$ where the investment cost can be calculated as: $Investment\ Cost\ = C_{eq} + C_{en} + C_l + C_f$ where C_{eq} is the cost of all developed sub-systems, C_{en} is the engineering cost, C_l is the labour and installation cost, and C_f is the financing costs related to installation. $Gain\ from\ Investment\ (GI) = \sum_{h=1}^{T}(CPE_{sav} + DR)$ where CPE_{sav} is the energy cost of primary energy savings and *DR* is the demand/response remuneration
Units	[-]
References	Benalcazar, P. Sizing and optimizing the operation of thermal energy storage units in combined heat and power plants: An integrated modelling approach. Energy Conversion and Management 242 (2021) 114255

Net present value (NPV)	
Description	$NPV = \sum_{t=1}^{T}\frac{GI}{(1+r)^t} - C_o$ where *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, and *r* is the discount rate (which should be based on available investment and/or inflation)
Units	[€]
References	Khamlich, I., Zeng, K., Flamant, G., Baeyens, J., Zou, C., Li, J., Yang, X., He, X., Liu, Q., Yang, H., Yang, Q., Chen, H. Technical and economic assessment of thermal energy storage in concentrated solar power plants within a spot electricity market. Renewable and Sustainable Energy Reviews 139 (2020) 110583

Payback period	
Description	Time in which the NPV (Net Present Value) equals 0. Simple payback period is the time in which the NPV equals 0 assuming r is set to 0
Units	[years]
References	Guo, S., Zhao, J., Wang, W., Yan, J., Jin, G., Wang, X. Techno-economic assessment of mobilized thermal energy storage for distributed users: A case study in China. Applied Energy 194 (2017) 481-486

Production cost	
Description	It refers to the costs incurred when manufacturing a good or providing a service. Production cost includes a variety of expenses
Units	[€]
References	European Project SWS-HEATING. Available online: http://www.swsheating.eu/ (accessed on 21 June 2021)

Specific cost of the storage	
Description	It defines the overall cost of a certain energy storage normalized on the total amount of energy it can deliver during its expected lifetime
Units	[€/MWh]

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References	Del Pero, C., Aste, N., Paksoy, H., Haghighat, F., Grillo, S., Leonforte, F. Energy storage key performance indicators for building application. Sustainable Cities and Society 40 (2018) 54-65

Generated cost saving	
Description	It is the expected cost saving generated by the energy storage system in a system. It must be referred to a certain period (e.g. day, season, year) which must be characterized by a specific number of working cycles
Units	[€]
References	Del Pero, C., Aste, N., Paksoy, H., Haghighat, F., Grillo, S., Leonforte, F. Energy storage key performance indicators for building application. Sustainable Cities and Society 40 (2018) 54-65

2.5 Environmental performance indicators

CO_2 emissions savings	
Description	$tCO2sav_t = \sum_{ec} FEsav_{ec} * CO2emf_{ec}$ where $FEsav_{ec}\left[\frac{kWh}{year}\right]$ is the final energy savings of the energy carrier: $FEsav_{ec} = FE_{hy,ec} - FE_{r,ec}$ where $FE_{hy,ec}$ is the final energy consumption of the energy carrier after the solution is implemented, and $FE_{r,ec}$ is the final energy consumption of the energy carrier in the reference case
Units	[tCO_2/year]
References	Eurostat, "Greenhouse gas emission statistics – emission inventories – Statistics Explained," 2017. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics

Greenhouse gas (GHG) emissions savings	
Description	$GHGsav_t = \sum_{ec} FEsav_{ec} * GHGemf_{ec}$ where $GHGemf_{ec}\left[\frac{tCO2eq}{kWh}\right]$ is the GHG emission factor of the energy carrier: $FEsav_{ec} = FE_{hy,ec} - FE_{r,ec}$ where $FE_{hy,ec}$ is the final energy consumption of the energy carrier after the solution is implemented, and $FE_{r,ec}$ is the final energy consumption of the energy carrier in the reference case
Units	[tCO_{2eq}/year]
References	European Environmental Agency (EEA), Air quality in Europe – 2015 report, 2015 ISO 14064 series – Greenhouse gases ISO 14067:2018 – Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification
NOx emissions savings	
Description	$tNOxsav_t = \sum_{ec} FEsav_{ec} * NOxemf_{ec}$ where $NOxemf_{ec}$ is the NOx emission factor of the energy carrier
Units	[tNO_xeq/year]
References	European Environmental Agency (EEA), Nitrogen oxides (NOx) emissions, 2018

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SOx emissions savings	
Description	$tSOxsav_t = \sum_{ec} FEsav_{ec} * SOxemf_{ec}$ where $SOxemf_{ec}$ is the SOx emission factor of the energy carrier
Units	[$tSO_x eq$/year]
References	Environmental Protection Agency (EPA), United States, Sulfur Dioxide Basics, 2018

Global warming potential (GWP)	
Description	It measures the amount of energy absorbed by the atmosphere due to the emissions of 1 ton of a gas with respect to the emissions of 1 ton of carbon dioxide (CO_2) over 100 years (GWP100) or 20 years (GWP20)
Units	[tCO_2/year]
References	Environmental Protection Agency (EPA), United States, Sulfur Dioxide Basics, 2018

2.6 Architectural indicators

Slip resistance	
Description	Evaluation and classification of the slip resistance of floorings which shall be used from residential to public spaces.
Units	R value from R9 (residential) to R13
References	CTE-SUA 1 UNE 41901:2017 EX – Surfaces for pedestrian transit. Determination of the slip resistance by pendulum friction method. Wet test. DIN 51130:2023 Testing of floor coverings – Determination of the anti-slip property – Workrooms and fields of activities with slip danger – Walking method – Ramp test (EN 16165:2023 – Determination of slip resistance of pedestrian surfaces – Methods of evaluation) and DIN 51097:2019 – Testing of floor coverings – Determination of the anti-slip properties – Wet-loaded barefoot areas; Walking method; Ramp test

Toxicity (POPs: Persistent Organic Pollutants)	
Description	Substances subject to restriction or elimination from the building materials
Units	mg/kg
References	Stockholm Convention on Persistent Organic Pollutants – Declaration. Convenio de Estocolmo, Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019 on persistent organic pollutants.

Acoustics	
Description	Acoustics and protection against noise in building design aspects
Units	dBA (decibel)
References	CTE-HR European Comission Joint Reserch Center: Level(s) indicator 4.4: Acoustics and protections against noise https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/2021-01/UM3_Indicator_4.4_v1.1_17pp.pdf ISO 717-2:2020 – Acoustics – Rating of sound insulation in buildings and of building elements. Part 2: Impact sound insulation ISO 9052-1:1989 – Acoustics – Determination of dynamic stiffness Part 1: Materials used under floating floors in dwellings ISO 11654:1997 – Acoustics – Sound absorbers for use in buildings – Rating of sound absorption

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Fire performance	
Description	Fire safety requirements
Units	[-]
References	Construction Products Regulation (CPR) National fire regulations for the use of wood in buildings - Worldwide review 2020, Birgit Östman BS 9991:2024 – Fire safety in the design, management and use of residential buildings. Code of practice ISO/CD TR 23801 – Fire safety engineering – Concept and example applications of risk-based fire safety design of buildings

2.7 Other performance indicators

Thermal sensation	
Description	According to ASHRAE, it is divided in 7 levels from 3 to -3 (hot, warm, slightly warm, neutral, slightly cool, cool, cold, respectively). It is function of gender and the number of hours of exposure, and it depends on the air temperature and the water vapour pressure
Units	[-]
References	ASHRAE, “HVAC Fundamentals”. Available online: https://www.ashrae.org/technical-resources/ashrae-handbook

Thermal complaints	
Description	$v_h = \frac{1}{2\pi}\sqrt{\frac{{\sigma_{\dot{T}_H}}^2 + {\sigma_{\dot{T}_S}}^2}{{\sigma_{T_H}}^2 + {\sigma_{T_S}}^2}} \exp\left(-\frac{1}{2}\frac{(\mu_{T_S} - \mu_{T_H})^2}{{\sigma_{T_H}}^2 + {\sigma_{T_S}}^2}\right)$ $v_l = \frac{1}{2\pi}\sqrt{\frac{{\sigma_{\dot{T}_L}}^2 + {\sigma_{\dot{T}_S}}^2}{{\sigma_{T_L}}^2 + {\sigma_{T_S}}^2}} \exp\left(-\frac{1}{2}\frac{(\mu_{T_S} - \mu_{T_L})^2}{{\sigma_{T_L}}^2 + {\sigma_{T_S}}^2}\right)$ where T_s is the space temperature, $\dot{T}_s$ is the rate of change of space temperature, T_H is the high-temperature at which a hot complaint occurs, T_L is the low-temperature at which a cold complaint occurs and $\dot{T}_H$, $\dot{T}_L$ are the respective rates of change. σ denotes standard deviation and μ mean value
Units	[-]
References	ASHRAE, “HVAC Fundamentals”. Available online: https://www.ashrae.org/technical-resources/ashrae-handbook

Predicted mean vote (PMV)	
Description	$PMV = (0.303e^{-0.36 \cdot M} + 0.028) \cdot L$ where M is the metabolic rate and L is the heat loss from human body
Units	[-]
References	ASHRAE, “HVAC Fundamentals”. Available online: https://www.ashrae.org/technical-resources/ashrae-handbook

Predicted percent dissatisfied (PPD)	
Description	$PPD = 100 - 95e^{-(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2)}$ where PMV is the predicted mean vote
Units	[%]
References	ASHRAE, “HVAC Fundamentals”. Available online: https://www.ashrae.org/technical-resources/ashrae-handbook

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Frequency of thermal discomfort (FTD)	
Description	The percentage of time during which the operative temperature exceeds the defined indoor temperature boundaries. The definition of these temperatures should comply with the adaptive thermal comfort criterion introduced in NBN EN 15251:2007 which defined three different categories of comfort.
Units	[%]
References	EN 16798-1:2019 Energy performance of buildings – Ventilation for buildings – Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics – Module M1-6F. Sicurella, G. Evola, and E. Wurtz. A statistical approach for the evaluation of thermal and visual comfort in free-running buildings. Energy & Buildings 47 (2012) 402-410

Intensity of thermal discomfort (ITD)	
Description	It is defined as the time integral of the positive difference between the current operative temperature and the upper limit of comfort (T_{lim}) $$ITD = \int_p \Delta T^+(t) \cdot dt$$ Where $\Delta T^+(t) = \{T_{op}(t) - T_{lim}\ if\ T_{op}(t) \geq T_{lim};\ 0\ if\ T_{op}(t) < T_{lim}\}$P is the occupancy period over which the integration is performed, and T_{op} is the operative temperature
Units	[°C·h]
References	V. Costanzo, G. Evola, L. Marletta, and F. Nocera. The effectiveness of phase change materials in relation to summer thermal comfort in air-conditioned office buildings. Build Simulation 11 (2018)1145-1161

Social acceptability	
Description	Qualitative assessment of the acceptability of innovative energy technologies
Units	[-]
References	Carbajo, R., Cabeza, L. F. Researchers' perspective within responsible implementation with socio-technical approaches. An example from solar energy research centre in Chile. *Renewable and Sustainable Energy Reviews 158* (2022) 112132. Lucas, H., Carbajo, R., Machiba, T., Zhukov, E., Cabeza, L. F. Improving public attitude towards renewable energy. Energies, 14 (2021) 4521.

3 Selection of key performance indicators

This section reports the results of the evaluation of PIs described above that, according to the methodology adopted, were ranked assigning a number according to their relevance.
From the list of PIs retrieved from various resources and listed in the section above, the selection was performed by expressing a preference to indicate the relevance of the PIs as:

- Not relevant (to be disregarded).
- Useful but not relevant.
- Useful.
- Very useful (KPIs).

The template of the questionnaire is shown in Table 1 as an example.

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Table 1. Example of the questionnaire

PI	Not useful at all	Useful but not relevant	Useful	Very useful (potential KPI)
Energy storage capacity				x
Energy density				x
Latent heat of fusion			x	

For each preference a score was assigned from 0 to 3 following the rule in Table 2.

Table 2. Scoring rule used for PIs evaluation

PI Relevance	Point
Not relevant (to be disregarded)	*0*
Useful but not relevant	*1*
Useful	*2*
Very useful (KPIs)	*3*

After collecting all the inputs and answer to the questionnaire, the only the PIs with a minimum total score of 11 were selected. The list of KPIs is shown in Table 3.

The results shows that a total of 29 KPIs were identified to evaluate difference performance of the BIOBUILD technology at material and/or building level. This list of the 29 relevant KPIs can inform the next stages of the BIOBUILD project in developing and evaluating products and services, as well as external stakeholders working on comparable (bio-based) products. Indeed, KPIs should represent the indicators where the project should be more focused, nevertheless this does not exclude that for some activities other performance indicators listed in this document can be evaluated.

Table 3. List of KPIs

KPI nº	Name	Level	European/international standards in wich KPI is related
1	*Energy storage capacity*	*Product*	*EN IEC 62923 series*
2	*Energy density*	*Product*	*ISO 52003-1*
3	*Specific heat capacity*	*Product*	*hEN 15459* *hEN 15316 series* *hEN 15603*
4	*Density*	*Product*	-
5	*Thermal conductivity*	*Product*	*EN 12667* *EN 12939*
6	*PCM melting temperature*	*Product*	*only standards for testing and characterization of phase change materials*
7	*Technology Readiness Level (TRL)*	*Product*	*ISO 16290*
8	*Cost*	*Product/Building*	*EN 15459*
9	*Durability (life cycle or design lifetime)*	*Product*	*CEN TC 38 standards* *CEN/TS 15083 series* *EN 350*
10	*Recyclability*	*Product*	*hEN 15804*
11	*Safety aspects*	*Product/Building*	*hEN 338, hEN 460*

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12	*Toxicity (POPs: Persistent Organic Pollutants)*	*Product*	*hEN 15251*
13	*Fire performance*	*Product*	*EN 13501*
14	*Seasonal coefficient of performance*	*Building*	*EN 15243*
15	*Annual heating and cooling demand per net useful area*	*Building*	*EN ISO 13790*
16	*Final energy use*	*Building*	*EN ISO 10211*
17	*Primary energy use*	*Building*	*hEN 15603*
18	*Energy savings*	*Building*	*EN ISO 13790 EN 15255*
19	*Thermal stability*	*Building*	*EN ISO 13789 EN ISO 10456*
20	*Thermal lag*	*Building*	*EN ISO 10456 EN ISO 13370*
21	*Operational expenditures (OPEX)*	*Building*	*EN 13986*
22	*Capital expenditure (CAPEX)*	*Building*	*hEN 338*
23	*Return on investment (ROI)*	*Building*	-
24	*Net present value (NPV)*	*Building*	-
25	*Payback period*	*Building*	-
26	*CO_2 emissions savings*	*Material/Building*	*ISO 13391 series prEN 15978-1*
27	*Greenhouse gas (GHG) emissions savings*	*Material/Building*	*ISO 13391 series prEN 15978-1*
28	*NOx emissions savings*	*Material/Building*	*ISO 13391 series prEN 15978-1*
29	*Global warming potential (GWP)*	*Material/Building*	-

4 Conclusions

Performance indicators (PIs) are fundamental to allow the comparison of the BIOBUILD solution with different technologies that can be used for building applications and evaluate the potential benefits in different aspects.

In this task different performance indicators suitable to be applied at material or building level were collected through a deep review of literature, projects and existing standards.
The selection of relevant parameters (KPIs) was then done considering the stakeholder perspective considering the main objectives of the project. Then a detailed questionnaire was developed and shared amongst the partners to express their preference indicating the relevance of the PIs.

The results shows that a total of 29 KPIs were identified to evaluate difference performance of the BIOBUILD technology at material and/or building level. These KPIs constitute a reference framework for monitoring progress and supporting decision-making across the different work packages of the project, including future demonstration activities, testing campaigns, environmental studies and product development.

The KPIs identified will ensure the implementation of the technical, environmental, and economic specifications in the BIOBUILID technology concept. KPIs should represent the indicators where the project should be more focused, nevertheless this does not exclude that for some activities other performance indicators listed in this document can be evaluated.

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Annex 1 Evaluation of performance indicators

This Annex reports the results of the questionnaire and the scoring to select the KPIs.

Technical performance indicators at material level

PI	Not useful at all	Useful but not relevant	Useful	Very useful (potential KPI)	Total score
Energy storage capacity			XX	XXX	13
Energy density		X	X	XXX	12
Latent heat of fusion		X	X	XX	9
Specific heat capacity			XX	XXX	13
Density			XXXX	X	11
Thermal conductivity				XXXXX	15
Temperature coefficient for thermal conductivity (optional, if conductivity is not constant)	X	XX	X	XX	10
Thermal effusivity		XX	XX	X	9
Packing factor		XX	X	X	7
Operating temperature		XX	XX	X	9
PCM melting temperature			X	XXXX	14
PCM hysteresis temperature difference		X	XXX	X	10
Technology Readiness Level (TRL)		X	XX	XX	11
Cost			X	XXXX	14
Availability		X	XXX	X	10
Durability (life cycle or design lifetime)			XX	XXX	13
Degradation		X	XX	XX	11
Recyclability			XX	XXX	13
Safety aspects		XX		XXX	11
Leachability of phase change material (PCM)			X	X	5
Susceptibility to bio-deterioration (stain and mould fungi)			XX		4

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Technical performance indicators at building/system level

PI	Not useful at all	Useful but not relevant	Useful	Very useful (potential KPI)	Total score
Seasonal coefficient of performance			XXXX	X	11
Demand Factor		XX	XXX		8
Annual heating and cooling demand per net useful area		X		XXXX	13
Final energy use		X	XX	XX	11
Primary energy use		X	XX	XX	11
Primary energy ratio (PER)		X	XX	X	8
Energy savings				XXXXX	15
Thermal stability			XXX	XX	12
Amplitude of temperature swing		X	XXXX		9
Thermal lag			XXX	XX	12
Thermal distribution		X	XXXX		9
Heat retention post-set point		X	XXX	X	10
Global daily energy reduction (GDER)		X	XXX	X	10

Economic performance indicators

PI	Not useful at all	Useful but not relevant	Useful	Very useful (potential KPI)	Total score
Operational expenditures (OPEX)			XX	XXX	13
Capital expenditure (CAPEX)			XX	XXX	13
Return on investment (ROI)			X	XXXX	14
Net present value (NPV)			XXX	XX	12
Payback period		X		XXXX	13
Production cost			X	XXXX	14
Specific cost of the storage		XXX	XX		7
Generated cost saving			XXXXX		10

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Environmental performance indicators

PI	Not useful at all	Useful but not relevant	Useful	Very useful (potential KPI)	Total score
CO_2 emissions savings		X		XXXX	13
Greenhouse gas (GHG) emissions savings		X	X	XXX	12
NOx emissions savings		XX		XXX	11
Global warming potential (GWP)			XXX	XX	12
SOx emissions savings		XX	XX	X	9

Architectural performance indicators

PI	Not useful at all	Useful but not relevant	Useful	Very useful (potential KPI)	Total score
Slip resistance	X	XX		XX	8
Toxicity (POPs: Persistent Organic Pollutants)			XX	XXX	13
Acoustics		XX	X	XX	10
Fire performance		X	X	XXX	12

Other performance indicators

PI	Not useful at all	Useful but not relevant	Useful	Very useful (potential KPI)	Total score
Thermal sensation		XXX	XX		7
Thermal complaints		XXX	XX		7
Predicted mean vote (PMV)		XXXXX			5
Predicted percent dissatisfied (PPD)		XXXX	X		6
Intensity of thermal discomfort (ITD)		X	XXX	X	10
Frequency of thermal discomfort (FTD)		XX	XXX		8
Social acceptability		XXX	X	X	8

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