D7.1 – Circular economy evaluation procedure/tool

Funded by the European Union

Deliverable Information Sheet

Version	1.0
Grant Agreement Number	101079957
Project Acronym	RE-SKIN
Project Title	Renewable and Environmental-Sustainable Kit for building Integration
Project Call	HORIZON-CL5-2021-D4-02-02
Project Duration	42
Deliverable Number	D7.1
Contractual Delivery Date	31/08/2024
Actual Delivery Date	02/10/2024
Deliverable Title	Circular economy evaluation procedure/tool
Deliverable Type	R
Deliverable Dissemination Level	PU
Work Package	7
Lead Partner	ENEL X
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History of changes

Version	Date	Comments	Main Authors
0.1	22/07/2024	First draft, establishing document structure	S. Arcieri (Enel X)
0.2	04/09/2024	Contribution input from all participants	A. Dalla Valle, C. Talamo, G. Paganin, N. Atta, M. Lavagna, A. Campioli (POLIMI)
0.3	12/09/2024	First version, incorporating input from all participants	S. Arcieri (Enel X)
0.4	13/09/2024	Quality review	F. Leonforte, C. Del Pero, R. Adhikari (POLIMI)

1.0	18/09/2024	Final version addressing all further comments	S. Arcieri (Enel X)

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Disclaimer

1. Executive summary

The aim of this deliverable is to show the methodology adopted for the development of Sustainability Dynamic Rating (SDR) tool to support the whole building retrofit intervention, from decision-making, design phase, operational as well as dismission phase.

The SDR tool represents a further development and optimization of the DSS tool designed under the EU Horizon 2020 project HEART. More in detail, the new release is able to provide dynamically, i.e., according to the different boundary conditions, the GWP impact along the whole life cycle of the building.

The document thus describes the different framework and requirements considered for the definition of the new tool, starting from the preliminary benchmarking activity, through the definition of evaluation areas and related KPIs, to the assignment of intermediate scores for the construction of the final score, illustrating the logical behind them.

2. INTRODUCTION

The application of the circular economy paradigm within the built environment presents several challenges, particularly in relation to the significant investments required for technological upgrade and the ambitious decarbonization targets and environmental objectives that must be met. The built environment contributes substantially to both embodied (materials, technologies, and processes) and operational energy consumption (building operation and services) and related carbon emissions. Embodied energy, which is the sum of all energy required to build a manufact, from the extraction of materials to construction, often poses a significant challenge in terms of reducing carbon footprints. Meanwhile, operational energy, related to the ongoing energy use of buildings, remains a critical focus in the context of decarbonization, where both technological and human behavioural factors are relevant. Balancing these factors while adhering to circular economy principles, which prioritize resource efficiency and waste reduction, requires innovative approaches and tools that can assess and optimize energy performance across the entire life cycle of buildings (from early design stages to dismantling and reuse and recycling).

The evaluation procedure and toolkit developed in the RE-SKIN represent the continuation and evolution of the research work initiated under the Horizon 2020 project HEART. The research undertaken in these projects has built on a foundation of rigorous exploration of potential modelling approaches for the building stock. A variety of these approaches were considered, informed by systematic reviews conducted in recent years by Kavgic et al. [1], Foucquier et al. [2], Fumo [3] and, more recently Chen et al. [4].

The models reviewed span from physics-based to data-driven [4], adopting categorisations such as white-box (detailed physics-driven modelling), grey-box (a combination of physical and statistical modelling), and black-box (statistical and machine learning, data-driven). Within the large variety of modelling approaches available at the state-of-the-art, the research community has placed growing emphasis on developing methodologies to effectively and reliably model buildings at scale, as evidenced by the review studies previously mentioned. Simultaneously, there is a concerted effort to ensure that the computing workload remains appropriate and commensurate with the objectives of the modelling process.

Concepts such as zoning [5], which involves the partitioning and decomposition of models, and algorithms like “shoe-boxing” [6], are becoming increasingly relevant in this context. These approaches allow for the simplification of building energy models, enabling their application at various scales (up to building stock and urban scale), while providing an adequate accuracy [7].

However, while the growing availability of building stock data and the advancement of computational tools have significantly improved the capabilities of energy models, applicable across different scales [8] (from single buildings to entire neighbourhoods and cities [6,7]), validation and calibration of models at scale remains challenging, due to the large variety of building geometries, physical properties, operational conditions, etc.

Following the research achievements discussed earlier, to maintain the reliability and scalability of building energy models, it is important to emphasize the key features that must be included in the modelling process. First, it is important to note that models must respect fundamental principles of energy and mass conservation, as well as other constraints. In addition, it is important that the results may be compared to those obtained from other tools or established methods, including validation cases.

In relation to the first point, the estimation of the components of the energy balance can be achieved through regression techniques, as demonstrated by Catalina et al. [9], Vesterberg et al. [10–12], and Manfren et al. [13,14]. Then, in relation to the second point, energy balance components can be analytically formulated in a manner analogous to semi-stationary balance conditions [14]. Subsequently, they can be compared [15,16] and calibrated with a dynamic energy balance model [17] to enhance accuracy of energy calculations by means of a better estimation of the parameters used in the analytical formulation.

As such, even in cases where some details of a building are unknown, it is possible to derive lumped or aggregated building properties estimates [18–20], ensuring continuity (between physics-driven simulation tools and data-driven methods) [21,22] and reasonable accuracy of the modelling process. These models can be calibrated [23] using these aggregated properties and can employ well-established statistical criteria developed and empirically tested in the field of Measurement and Verification (M&V) [24], to evaluate the models' goodness of fit.

While M&V techniques and applications have been consolidating in various protocols for field application, with the definition of different levels of detail in modelling [25,26], potential advances have been extensively reviewed in recent years by Grillone et al. [27,28], Alrobaie and Krarti [29], Fu [30], and Manfren et al. [31,32].

In both the HEART and RE-SKIN projects, the chosen modelling approach integrates simulation tools, used as a synthetic data generating process [33,34] and data-driven methods able to model both simulated and measured performance, favouring techniques that are intrinsically interpretable [35]. This means that the models are designed to be intelligible in human terms without the need for post-hoc methods, such SHAP or LIME [36] to explain their characteristics and results. Interpretability is crucial from many points of view [32] and, in particular, to build trustworthy models and ensure that results can be directly interpreted in light of physical principles and analytical relationships.

In this respect, recent research has demonstrated that many of the concepts employed in the HEART and RE-SKIN models can be effectively applied and validated at scale, as shown by Staffel et al. [37], using case studies at global scale and Eggimann and Fiorentini [38], using building archetypes developed by the U.S. Department of Energy and the Pacific Northwest National Laboratory.

These examples, together with the large amount of evidence provided in reviews [27–32], confirm the robustness of the methods employed in RE-SKIN project. Overall, the models implemented are grounded in physical principles, outlined before, and supported by an interpretable data-driven formulation, provide a reliable framework for assessing and optimizing building energy performance, within a circular economy framework.

Further details on the evaluation procedure and toolkit development are elaborated later in this document, providing a comprehensive overview of the methodologies and tools that have been developed as part of the research.

3. METHODOLOGY

This chapter describes the methodological process behind the design of the Sustainability Dynamic Rating (SDR) tool to support the whole building retrofit intervention, from decision-making, through design phase, to operational phase.
First of all, the benchmarking analysis has been carried out on certifications, legislative requirements, frameworks and assessment tools in the building efficiency sector.
According to this, the main recurring area of analysis have been identified and included in the new tool. Finally, the definition of KPIs, carried out through a process of progressively skimming the complete list of KPIs extrapolated through benchmarking on the various models, has been performed.

There are three areas of analysis identified, each of which contains different KPIs:

1. **Energy**, refers to operational energy, which is the energy used for the daily operation of a building.

2. **LCA**, refers to embodied energy, which is the total amount of energy required to produce, transport, install, maintain, and dispose of materials used in a building or product throughout its life-cycle. This includes the energy consumed in extracting raw materials, processing them, transporting them, installing them, and finally demolishing and disposing of them.

3. **Circular economy**, refers to the circularity attitude, which is the design and management approach that aims to maximize the efficient use of resources and minimize waste throughout the building life-cycle. This concept includes various practices, such as designing for disassembly, waste management, durability and adaptability, etc.

Leveraging these KPIs and the data input by the framework user, the model returns as output a single indicator, in terms of $CO_{2\,eq}$, that quantifies sustainability, taking into account operational and embodied energy, as well as component maintenance and disposal cycles.

The resulting SDR (Sustainability Dynamic Rating System) leverages cloud technology to analyse and manage the entire life cycle of buildings renovated with RE-SKIN components, aiming to enhance the environmental sustainability performance over the whole life-cycle and beyond in view of circular economy practice. The platform generates real-time analysis that provide insights into sustainability performance, highlighting areas for improvement. It allows collaborative features across various stakeholders and users to model different scenarios for understanding potential impacts and outcomes, supporting informed decision-making. As integral part of SDR and in conjunction with DSS and BEMS, the aim is to find the optimal technological-constructive solution for the building, taking into account the specific context. A framework flowchart for SDR methodological process is shown in Fig. 1.

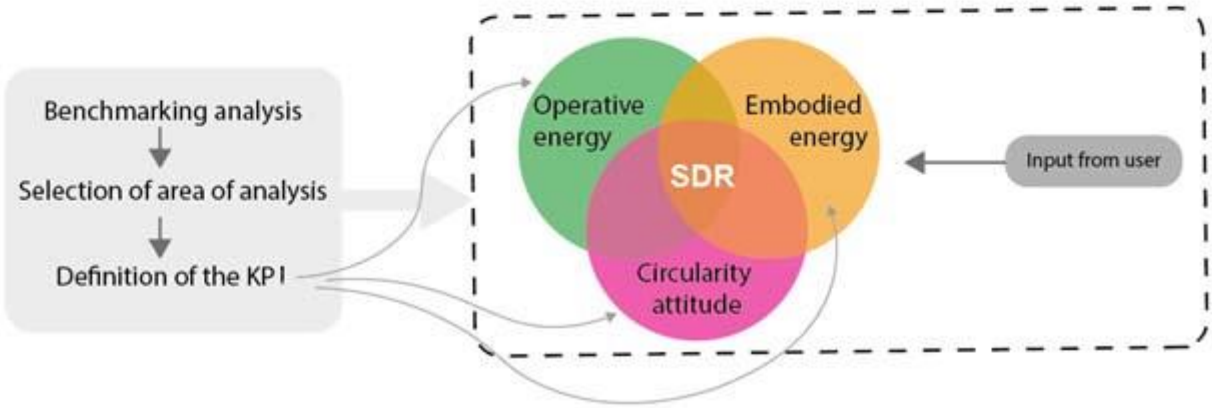

Figure 1. Framework flowchart

3.1. Benchmarking analysis

In order to identify the main area of interest that should be included in the RE-SKIN tool, a benchmark analysis of the relevant existing building sustainability assessment protocols, have been performed.

The purpose of the benchmarking analysis is to provide an overview of recurring themes and areas of analysis, as proposed by the guidelines, and to enable the definition of a KPI system that reflects the needs of the RE-SKIN project, while ensuring a reference framework.

Key important methodological decisions have been made regarding the selection of benchmark study objects to be included in the analysis and the type of information that should be gathered for each benchmark object.

Benchmark objects selected include:

- buildings' sustainability certifications;
- buildings' sustainability frameworks;
- EU and country level sustainability-related legislative requirements for buildings and construction works;
- buildings' sustainability assessment tools.

To perform benchmarking analysis, specific criteria are evaluated to determine if the evaluated benchmark objects are relevant to the solutions proposed by the RE-SKIN project.
The following parameters have been examined for each benchmark object:

- general information (the owner and the developer of the item, the year of introduction, …);
- model application criteria (scope and approach, scale of application and building typology considered, …);
- key energy-related areas and KPIs;
- key GHG emissions-related areas and KPIs;
- key circular economy-related areas and KPIs;
- other sustainability-related areas;
- references.

The benchmark analysis was conducted on 20 framework/certification/protocol reported in **Errore. L 'origine riferimento non è stata trovata.**. According to the assessment of the official documentation, the following results could be reported:

- 35% of the models analysed are necessarily used by expert figures;
- 95% of the models analysed are defined by a qualitative/quantitative approach to building assessment;
- 70% of the models analysed include evaluation metrics for renovation/refurbishment of building life-cycle phase;
- 75% of the models analysed include a construction materials assessment area.

Among others, some framework/certification/protocol (highlighted in green) can be considered the most consistent with RE-SKIN goals. In such respect a brief description of them is reported and considered in the development of RE-SKIN tool.

Legend
CED: Cumulative Energy Demand | LCA: Life Cycle Assessment | TQA: Total Quality Assessment
ECO: economic | SOC: social | ENV: environmental
⚡: Energy and emissions | ♻: Circularity

	Nature	Typology	Category	Paid / Open access	Sustainability scope	Environmental assessment areas
#1 BREEAM	Certification	Benchmarking	TQA	Paid	ENV / SOC / ECO	⚡ ♻
#2 LEED	Certification	Benchmarking	TQA	Paid	ENV / SOC / ECO	⚡ ♻
#3 APE	Legislative requirement	Benchmarking	CED	Paid	ENV / ECO	⚡
#4 EN 15084	Framework	Assessment	LCA	Paid	ENV	⚡ ♻
#5 Common Carbon Metric	Framework	Assessment	LCA	Open access	ENV	⚡ ♻
#6 DGNB Zertifikat	Certification	Benchmarking	TQA	Paid	ENV / SOC / ECO	⚡ ♻
#7 Passivhaus	Certification	Benchmarking	CED	Paid	ENV	⚡
#8 CAM	Legislative requirement	Assessment	LCA	Open access	ENV	⚡ ♻
#9 EPBD	Legislative requirement	Assessment	CED	Open access	ENV	⚡
#10 EU Taxonomy	Legislative requirement	Benchmarking	CED	Open access	ENV / SOC / ECO	⚡ ♻
#11 SPIRE Smart Buildings	Certification	Benchmarking	TQA	Paid	ENV / SOC / ECO	⚡
#12 Level(s)	Framework	Assessment	TQA	Open access	ENV / SOC / ECO	⚡ ♻
#13 Circular Buildings Toolkit	Framework	Benchmarking	TQA	Open access	ENV / SOC / ECO	♻
#14 SBTool	Framework	Benchmarking	TQA	Open access	ENV / SOC / ECO	⚡ ♻
#15 New European Bauhaus	Framework	Assessment	TQA	Open access	ENV / SOC	⚡ ♻
#16 The NZC Buildings Commitment	Framework	Assessment	CED	Open access	ENV	⚡
#17 LBC	Certification	Benchmarking	TQA	Paid	ENV / SOC / ECO	⚡ ♻
#18 HEART	Assessment tool	Assessment	CED	N.D.	ENV	⚡
#19 Enel X MASA	Assessment tool	Assessment	LCA	Paid	ENV	⚡ ♻
#20 Enel X CE Report	Assessment tool	Benchmarking	CED / LCA	Paid	ENV	⚡ ♻

Table 1. Benchmarking results overview

The **Energy Performance of Buildings Directive (EPBD)** aims to improve the energy efficiency of buildings within the European Union. The directive sets out measures to achieve a highly energy-efficient and decarbonized building stock by 2050. Key points include: renovation of buildings; energy performance standards; national plans; support for vulnerable consumers; digitalization of energy systems; infrastructure for sustainable mobility.

The **EU Taxonomy** is a classification system designed to guide investments towards sustainable economic activities. It helps identify which activities are environmentally sustainable, supporting the EU's climate and energy targets for 2030 and the European Green Deal objectives.

Level(s) is a European framework for assessing and reporting on the sustainability performance of buildings. It provides a common language and set of indicators to measure and improve the environmental impact of buildings throughout their life cycle.

The **New European Bauhaus** is an initiative by the European Union that combines sustainability, aesthetics, and inclusiveness to create beautiful, sustainable living spaces. It aims to bridge the gap between science, technology, art, and culture to address environmental and social challenges.

It supports the European Green Deal by promoting innovative design and construction practices that prioritize sustainability and social inclusion.

The HEART project (Holistic Energy and Architectural Retrofit Toolkit) is an H2020 project, already concluded, aimed at improving energy efficiency in buildings. It focuses on retrofitting existing buildings to make them more energy-efficient and sustainable. The project involves a toolkit that integrates various technologies like ICT, BEMS, HVAC, and renewable energy systems to transform buildings into smart, energy-efficient structures.

MASA (Material Sustainability Assessment) is a framework developed by Enel X to assess the level of sustainability of materials and components used in construction and renovation sites, in order to promote the increase of environmental sustainability performance in construction-related activities. The MASA model is able to fulfil a series of objectives: support sustainable procurement strategies and targets, providing a detailed and aggregated view of the sustainability of materials and components; provide a reporting tool which can be used at the end of the interventions to collect, cluster and communicate the sustainability characteristics of the materials selected for the building; support in creating a database of sustainable materials and components.

The **Circular Economy (CE) Report** by Enel X is an assessment model aimed at analysing and measuring the circularity of a company's energy use and operations. It identifies actions needed to enhance sustainability and transition from a linear to a circular economic model. This report helps companies improve their environmental impact by focusing on resource efficiency, waste reduction, and sustainable practices. The calculation model underlying the CE Report is a recognized certification framework and has been accredited by Accredia.

3.2. Assessment areas definition

The defined process to evaluate the areas of analysis started directly from the results of the benchmarking analysis. Follows a comprehensive list of the implemented steps:

1. identification of the main areas of analysis and related KPIs of the selected models;
2. standardization of these areas according to the KPIs included in each of them;
3. definition of 7 new areas of analysis (4 related to energy and 3 related to circularity) linked to all the metrics considered by the models under analysis.

The idea behind the definition of the new areas of analysis is based on the criteria of their recurrence, even in different forms, in most of the models examined, and their absolute relevance for the sustainability assessment of a building. This approach made it possible to identify the main dimensions, basis for the development of a robust and comprehensive assessment tool.

Thus, the list of newly designed areas is reported below:

- **energy consumption**: this area focuses on assessing the building's overall energy consumption, including the energy needed for heating, cooling, hot eater, lighting and other uses;
- **energy users and efficiency**: energy efficiency refers to the building's ability to use energy optimally, reducing waste and losses. This area of analysis includes thermal insulation, the adoption of high-efficiency heating and ventilation and air-conditioning (HVAC) systems;
- **monitoring**: this area covers the implementation of monitoring and control systems for real-time assessment of energy consumption and building operation crucial to facilitate transition of the entire energy system;
- **renewable energy**: the adoption of renewable energy sources is fundamental to the sustainability of buildings. This area of analysis assesses the building's ability to integrate and utilize energy from renewable sources, both produced on-site or purchased off-site;
- **sustainable construction management**: this area of analysis focuses on the "sustainability by design" of buildings and related components. This includes the presence of environmental studies and labels and compliance with sustainability standards, design for end-of-life extension and easy maintenance;
- **sustainable inputs**: the analysis of sustainable inputs concerns the origin and composition of materials and resources used for the building retrofitting. Specifically, material origin accounts for materials' production processes and distinguishes virgin materials, recycled materials and reused materials, in terms of amounts, GHG emissions and embodied energy. Material composition accounts for the use of bio-based materials;
- **reuse and recycle**: this area focuses on the possible end-of-life paths for demolition wastes at building's end of life or renovation. It takes into account potential reuse, recycle or disposal to landfill and related GHG emissions.

3.3. Key Performance Indicators Definition

The definition of the Key Performance Indicators (KPIs) to be implemented in the new building sustainability assessment model was based on the results of the benchmarking analysis. As with the definition of the analysis areas, a specific methodology was followed.

During the first step, all the recurring KPIs of the analysed models were identified. These KPIs were standardized in order to use the same terminology to assess identical quantities. Furthermore, the KPIs were divided according to the areas previously identified.

Next, an evaluation of the KPIs was carried out to ensure that all the main aspects of the buildings and interventions involved by RE-SKIN were covered. During this phase, the overall list of KPIs was supplemented or skimmed according to the specific needs of the project.

RE-SKIN highlights how the ultimate goal of the framework is to return a single indicator, in terms of CO_2 eq, that quantifies sustainability, taking into account operational and embodied energy, as well as component maintenance and disposal cycles. In support of this indicator, further indicators suggested by Level(S) framework have been provided.

The KPIs chosen for the framework can be grouped into three groups: those related to energy, those related to LCA analysis, and those related to circularity.

4. MODEL/TOOLKIT DESCRIPTION

The effectiveness of the entire RE-SKIN system is ensured by an ICT platform that integrates the Decision Support System (DSS), Building Energy Management System (BEMS), and Sustainability Dynamic Rating (SDR) tool. These tools support the building retrofit intervention in all its phases: from initial decision-making, through the design phase, to the operational phase and end-of-life phase. In particular, the Sustainability Dynamic Rating (SDR) combines the principles of the Circular Economy with a thorough environmental impact analysis through Life Cycle Assessment (LCA), offering a dynamic and holistic rating system that measures and promotes sustainability across multiple dimensions.
The life cycle cloud-based platform leverages cloud technology to analyse and manage the entire life-cycle of buildings renovated with RE-SKIN components, aiming to enhance environmental sustainability performance throughout the whole life cycle and beyond, in line with circular economy practices. The platform generates real-time analyses that provide insights into sustainability performance, highlighting areas for improvement. It allows collaborative features among various stakeholders and users to model different scenarios, understand potential impacts and outcomes, and support informed decision-making. As an integral part of the SDR and in conjunction with the DSS and BEMS, the goal is to find the optimal technological-constructive solution for the target building, taking into account the specific context.

The tool is divided into three sections: the first dedicated to energy, understood in terms of consumption, uses and efficiency level, the second dedicated to Life Cycle Assessment, and the third dedicated to circular economy, with specific focus on material circularity.

4.1. Energy

This section lists and describes the energy-related KPIs used within the framework (Table 2).

KPI	Description	UoM
Energy demand per unit of surface area – Total	This indicator measures the amount of energy (both electrical and thermal) consumed by the building related to its total floor area. It provides an indication of the level of energy consumption relative to the building's area and allows energy efficiency comparisons between different buildings before and after renovation for the same building. By measuring energy consumption per unit area, it is possible to identify buildings with high levels of energy consumption relative to their size, which could indicate inefficiencies or energy performance problems. A low value indicates an energy efficient building, as it consumes less energy for the same floor area than other buildings. On the other hand, a high value suggests high energy consumption related to floor area, indicating a need to take measures to improve energy efficiency and reduce consumption.	[kWh/m^2]
Energy demand per unit of surface area – Heating	This indicator measures the amount of energy (both electrical and thermal) consumed for heating the building related to its total floor area. The energy used for heating is a significant factor in the total energy consumption of a building, and measuring it allows us to assess the efficiency and adequacy of the building's heating systems. A low value indicates high energy efficiency in heating the building, which can be the result of good design and thermal insulation practices as well as efficient heating systems. Meanwhile, a high value suggests inefficiencies in the heating system, such as heat loss through building envelope (no/poor insulation), bad heat distribution systems or the use of obsolete equipment.	[kWh/m^2]
Energy demand per unit of surface area – Cooling	This indicator measures the amount of electrical energy consumed for cooling the building related to its total floor area. Energy consumption related to cooling is a significant factor in the overall energy consumption of a building, especially in regions with hot climates or during the summer season. Measuring energy consumption for cooling per unit of surface area allows the evaluation of the efficiency and adequacy of the building's cooling systems. A low value indicates high energy efficiency in cooling the building, which can be the result of proper design of building envelope (thermal insulation), the use of efficient cooling systems,	[kWh/m^2]

	and appropriate energy management practices. On the other hand, a high value indicates high energy consumption, suggesting insulation defects, inefficiencies in the cooling system, inefficiencies in the distribution of cooled air, or the use of outdated equipment.	
GHG emissions per unit of surface area – Total	In the scope of building's sustainability assessment, it is essential to track GHGs emissions related to operational activities. The indicators included in the model relate the emissions to unit of surface area: high values reflect carbon intensive activities and indicate room for efficiency interventions with high savings potential.	[kg CO_{2eq}/m^2]
Share of real time/nearly real time monitored energy consumption	The availability of real time consumption data fosters energy consumers' awareness and gives the opportunity to implement good consumption practices and reduce energy wastes; it is fundamental for the activation of demand response mechanisms and can be used to evaluate the energy efficiency interventions.	[%]
Electricity energy demand - Share of renewable energy	The share of renewable electricity demand over total electricity demand is a renowned indicator used to assess the level of sustainability of energy consumption whether it is global, national, regional, local, or building level. This indicator is a proxy of the fossil fuels avoided consumption and allows to estimate GHG emissions reduction associated to it. Renewable energy can either be generated on site or purchased off-site. The former case measures the contribution of the building to generated distribution; the latter reflects electricity purchasing contracts or the national energy mix. Increasing the share of renewable energy consumption is a part of the energy agenda in most countries and it is essential toward net zero European and national targets.	[%]
Electricity supplied to grid/other users' renewable energy per unit of surface area	The amount of energy per square meter sourced to the grid or other users is given by the difference between production and direct self-consumption (of the locally installed plant) related to building's surface. This indicator measures the contribution of the building to the local availability of clean energy. The same indicator is also declined at the intervention level to account for new installation or revamping of existing plants.	[kWh/m^2]

Table 2. Energy-related KPIs

4.2. LCA

The Life cycle platform assesses the environmental sustainability based on LCA, performed in compliance with Level(s), the European framework for sustainable buildings. Here, special attention is paid to the core indicator *"1.2 Life cycle Global Warming Potential"*, integrating the indicator *"1.1 Use stage energy performance"*, both referred to the macro-objective *"1. Greenhouse gas emissions along a building's life cycle"*. Moreover, the macro-objective *"2. Resource efficient and circular material life cycles"* is covered for the indicators *"2.1 Bill of quantities, materials and lifespans"*, *"2.2 Construction and demolition waste"*, *"2.3 Design for adaptability and renovation"* and *"2.4 Design for deconstruction"*, by including in the Life cycle platform all issues evaluable according to LCA method (they are considered in the LCA results, but the platform does not provide the reporting format defined by the specific Level(s) indicators). Note that, in order to go a step further, the focus is on cradle-to-grave Life Cycle Assessment (LCA) involving other impact categories than GWP.

In the following paragraphs, an overview of the LCA-based platform is provided, reporting a description of the key issues:

- LCA goal
- LCA scope
- LCA system boundaries
- LCA reference study period
- LCA indicators
- LCA software and database
- LCA data quality
- LCA platform user input (mandatory and optional)
- LCA platform application

4.2.1 LCA goal

The platform allows the user to perform an LCA analysis at building level, by testing the implementation of the RE-SKIN toolkit for retrofitting existing buildings and evaluating the environmental impacts associated with the entire life-cycle of the building: from material extraction to end-of-life.

This assessment helps in providing a holistic view of retrofitted building environmental performance and minimizing the overall environmental footprint of the building intervention, with the aim to improve energy efficiency, comfort and sustainability with a long-term vision towards circularity and find between different scenarios the solution able to optimize material flow (embodied emissions) and energy performance (operational emissions) during the whole life-cycle.

In this framework, the key goals of the LCA study are:

- Understanding environmental impacts: The primary goal is to quantify the environmental impacts of the retrofitted building across the various life-cycle phases (production, construction, operation, maintenance and end-of-life). In particular, the focus is on Global Warming Potential (GWP), but showing also the additional environmental indicators.
- Supporting decision-making: LCA results inform architects, engineers and developers in making environmentally responsible decisions, balancing material selection with energy efficiency improvements and sustainable waste practices.
- Comparing alternatives: the LCA platform is used to compare different retrofit and circularity scenarios based on the RE-SKIN toolkit, helping stakeholders to select the option with the least environmental impact.

4.2.2 LCA scope

The LCA analysis is intended for assessing the environmental impacts associated with the application of RE-SKIN toolkit.

Accordingly, the functional unit is the retrofitted building under study by the user of the platform, considering the set of technological components developed within RE-SKIN project for retrofitting the building and described in the Table 3. Note that the existing building is out of scope and thus not evaluated in the LCA study where the focus is exclusively on the new integrations. Different typologies of buildings (e.g., residential, office, commercial) could be evaluated according to user needs.

The different technological solutions included in the RE-SKIN toolkit are pre-set in the platform with the specific reference units (e.g., m^2 for façade system, n° of plant items), considering the whole life cycle.

Building parts	**Building elements**	**Technological solution**
Shell (substructure and superstructure)		
Load bearing structural frame	Frame (beams, columns and slabs)	

	Upper floors	
	External walls	
	Balconies	
Non-load bearing elements	Ground floor slab	
	Internal walls, partitions and doors	
	Stairs and ramps	
Facades	External wall systems, cladding and shading devices	Multifunctional prefabricated façade system is designed with a modular structure to cover the existing building, adding the outer layers of cladding, waterproofing and insulation. It is composed of sandwich panels interconnected by means of tongue-and-groove joint and installed over an aluminium substructure with 98% recycled content. The sandwich panels consist of a core of a novel biosourced polyurethane (bioPUR) foam, with two coating layers made of Greencoat sustainable steel. While the metallic sheet inner and outer layer are of 0.45 mm and 0.70 mm respectively, the bioPUR foam varies depending on expected performance as the following range: – 8 mm – 10 mm – 12 mm
	Façade openings (including windows and external doors)	Window retrofit prioritise the updating of existing windows to improve their energy efficiency, by the installation of window film solutions of different types: – Low-e film – Sun control film As last alternative, it is planned the replacement of existing windows as follows: – new PVC frame and new double insulated glass unit
	External paints, coatings and renders	The external coating is integrated into the multifunctional prefabricated façade system (see above)
Roof	Structure	
	Weatherproofing	Building-integrated photovoltaic-thermal (BIPVT) system is designed with a modular structure to be integrated in common sloped

		roofs, replacing the external covering, waterproof and insulation layers. It jointly integrates the PV modules (see detail below) and the prefabricated sandwich system, same as facades and composed of bioPUR foam. A ventilated air gap is placed between the PV module and sandwich panel, allowing airflow.
Parking facilities	Above ground and underground	
Core (fittings, furnishings and services)		
Fittings and furnishings	Sanitary fittings	
	Cupboards, wardrobe sand worktops	
	Floor finishes, coverings and coatings	
	Skirting and trimming	
	Sockets and switches	
	Wall and ceiling finishes and coatings	
In-built lighting system	Light fittings	
	Control systems and sensors	
Energy system	Heating and cooling plant and distribution	DC heat pump is designed to stay inside the building and take in air source from the outside. It is air-to-water and it is supplied 800VDC from MIMO converter, demanding 400ADC for compressor back up and 230ADC for control systems and indoor heat exchanger. Required air source temperature is -25°C to 45°C and required air volume is 5000 - 6000m^3/h. Heating and cooling capacity reach up to 18kW and average COP is 3.5 - 4.
	Radiators	Smart fan-coils are conceived to substitute radiators. The units operate as small water-to-air heat pumps, by extracting or releasing heat to the hydronic network and thus providing heating/cooling/dehumidification. They use a DC compressor to

		increase/decrease the temperature of the water coming from the centralized DC heat pump, according to the room's energy demand.
	Electricity generation	Refurbished PV modules are installed within the hybrid building-integrated photovoltaic-thermal (BIPVT) roofing system. They derive from a refurbishing process that allows worn-out components to be reused, avoiding their disposal. At present, it is a 3 bus-bar PV module integrating 60 polycrystalline cells (6 inches each), with a nominal power of 255 Wp. The module has an aluminium frame which encloses a glass-back sheet laminate. The front glass is tempered and has a thickness of 3.2 mm.
	Electricity distribution	Multi-input/multi-output (MIMO) converter allows to interface different energy sources and manage the electrical power flow between the roof PV panels, battery system, heat pump, fan coils and EV chargers, by supplying various loads (DC and AC). The converter configuration is designed to ensure high conversion efficiencies, limited size/weight, and standalone operation. It is composed of two power converters: a 4 leg AC-DC 15-20 kW inverter to interface the utility grid and a bidirectional 10 kW DC-DC converter to interface the battery. Repurposed battery system is made by a set of reused batteries, dealing with a repurposed process in order to give a second life to the battery cells extracted from Electrical Vehicles (type LEV40 from Mitsubishi Outlander PHEV). The cells are originally manufactured with a nominal cell voltage of 3.75 V. The battery system is composed of 18 battery banks for a total of 144 cells, each weighing 1.4 kg, installed in a cabinet and managed by a Battery Management Systems (BMS). The weight (including BMS and excluding cabinet) is of 208.6 kg and the nominal capacity is 16.2 kWh from full charge.
Ventilation system	Air handling units	
	Ductwork and distribution	
Sanitary systems	Cold water distribution	
	Hot water distribution	
	Water treatment systems	

	Drainage system	
Other systems	Lifts and escalators	
	Firefighting installations	
	Communication and security installations	
	Telecoms and data installations	
External works		
Utilities	Connections and diversions	
	Substations and equipment	Electric Vehicles (EV) chargers are proposed in two different types of charging infrastructures to meet the building user needs: – a wall mounted solution (type A) capable of connecting one vehicle at a time, with a power ranging from 7 kW to 22 kW and available in two different versions: – Waybox cable – Waybox socket – a free-standing solution (type B) capable of charging up to two vehicles simultaneously, with a power of up to 22 kW and available in two different versions: – JuicePole Single/Three-phase – JuicePole Three/Three-phase
Landscaping	Paving and other hard surfacing	
	Fencing, railings and walls	

Table 3. Overview of building parts, building elements and technological solution

As discussed, the life cycle cloud-based platform focuses on deep retrofits that occur when asset has reached a certain stage of its life-cycle. Indeed, it involves major equipment replacement, complete renewal of the building envelope (facade and windows) and result in substantial reductions in net energy.

4.2.3 LCA system boundaries

The system boundary is "cradle-to-grave" as defined by EN 15978 *"Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method"*, namely from the production of building materials to the end of the building useful life and the subsequent demolition and recovery of the building materials. Table 4 below explain the life cycle stages and modules included into the Life cycle cloud-based platform for building retrofitting (materials of existing building are out of the system boundary).

Life cycle stage	Modules	Description
Production stage	A1-A3	The boundary covers the "cradle-to-gate" processes for the RE-SKIN components used in the construction for the building retrofit.
	A4	The construction process stage covers the processes from the manufacturing plant of the different RE-SKIN components to the practical completion of the construction work.
Use stage	B2 B4	The use stage covers the timeframe ranging from the completion of construction work to the final deconstruction/demolition of building. It includes the use of resources and activities for the maintenance and replacement of RE-SKIN components, in relation to the specific service lifespans.
	B6	The boundary shall include energy used by building-integrated technical systems during the operation of the building.
	B7	The operational water usage is out of scope.
End of life stage	C2-C4	The end-of-life stage starts when the different RE-SKIN components are decommissioned. As appropriate, the demolition/deconstruction is considered as a multi-output process that provides a source of materials, products and building elements that are to be discarded, recovered, recycled or reused. The demolition of existing buildings is out of scope.

Benefits and loads beyond the system boundary	D	Components for reuse and materials for recycling and energy recovery are considered as potential resources for future use. Module D quantifies the net environmental benefits or loads resulting from reuse, recycling and energy recovery resulting from the net flows of materials and exported energy exiting the system boundary. In compliance with LCA standards, this module is always displayed separately.

Table 4. Life cycle stages

Addressing the whole life cycle, the boundary includes both the assessment of operational emissions (those associated with the energy used for heating, cooling and supplying electricity to a building) and embodied emissions (those resulting from the construction, maintenance, replacement and deconstruction of building). As usual, emissions are accounted for in the life-cycle stage where they occur. However, in RE-SKIN project, the retrofit is intended as a new life for the building, allocating the impacts associated with the retrofit of existing building with RE-SKIN toolkit to the production stage (not the use stage), in order to offer distinct impacts for the activities occurred during the operational service (e.g., maintenance and replacement). The recovery of demolition or strip out materials from existing building is considered outside the system boundary, since the platform cannot consider the infinite variables of existing products/components.

Furthermore, to handle the multi-functionality of the second life RE-SKIN components included into the toolkit – namely the repurposed battery system and the refurbished PV panels – the cut-off allocation method is pursued in compliance with the specific standards of construction sector, both EN 15804 (at product level for Environmental Product Declarations) and EN 15978 (at building level for the assessment of whole environmental performance). In facts, because of the impacts are assigned to each life-cycle stage, it is crucial to clearly specify what is included into the system boundaries in those cases where products are recovered for supporting closed-loop practices. Here, the cut-off allocation consists in fully assigning the manufacturing and end-of-life impacts to the first life and assessing the impacts of the second life. The delivery of the product (as waste) is considered as a zero-impact input for the new life, evaluating only the impacts necessary to regenerate it (starting from the transport from the sorting plant to the remanufacturing plant). This is an input-oriented method, which assess the impacts occurred within the system boundary under study, by allocating impacts directly to the product generating them. In this way, the cut-off fully assigns to the first life of components (original battery system and PV panels): the extraction of raw material, the production process, the first use phase and the waste disposal. It allocates instead to the second life the impacts of transport to the remanufacturing plant, repurposing/refurbishment process, second use phase and disposal, when covering the full life cycle. Accordingly, materials reuse rewards the second life in terms of reduced environmental impacts, not accounting in the system boundary the production of both battery system and PV panels, but only the performed repurposing and refurbishment process.

4.2.4 LCA reference study period

The reference study period, namely the period over which the time-dependent characteristics of the building are analysed, is of 50 years as required for the Level(s) assessments. Note that the reference study period may differ from the required service life of both building and the related components and it is considered as follows:

- Impacts of production stage (A1-A3), construction stage (A4-A5) and end-of-life stage (C1-C4) are independent of the value of the reference study period;
- Impacts of use stage (B1-B6) and benefits and loads beyond the system boundaries (D) are proportional to the length of the reference study period. The opposite applies when results are normalised to m^2 per year.

4.2.5 LCA indicators

In line with Level(s) and in compliance with the related LCA requirements, the assessment of the environmental performance follows the EN 15804 +A2 standard, selecting characterisation results to evaluate potential impacts. In particular, **Global Warming Potential** (GWP) is the key indicator in the spotlight. It measures the greenhouse gas (GHG) emissions associated with the building at different stages along the life cycle, from the "cradle" (the extraction of the raw materials that are used construction the building) through to the "grave" (the deconstruction of the building and how to deal with its building materials, i.e. recovery, reuse, recycling and disposal), and thus the related effects on climate change. Carbon emissions embodied in building materials are brought together with direct and indirect carbon emissions from use stage performance, namely energy consumption (water consumption is out of scope). In this way, the cradle to grave thinking allows for building design solutions that seek the optimum balance between embodied carbon and use stage carbon emissions. Indeed, it is worth mentioning that buildings are significant material bank, being considered as repository for carbon intensive resources over many decades and so calling for design that facilitate the future recovery, reuse and recycling at the end of the building life. GWP of the greenhouse gases emitted are expressed in terms of $kgCO_2$ equivalents and broken down into the different subcategories shown in the Table 5 below.

Impact category	Indicator	Unit
Climate change - total*	Global Warming Potential total (GWP-total)	kg CO_2 eq./m^2

Climate change - fossil	Global Warming Potential fossil fuels (GWP-fossil)	kg CO_2 eq. /m^2
Climate change - biogenic	Global Warming Potential biogenic (GWP-biogenic)	kg CO_2 eq. /m^2
Climate change - land use and land use change	Global Warming Potential land use and land use change (GWP-luluc)	kg CO_2 eq. /m^2

Table 5. LCA GWP indicators

* The total global warming potential (GWP) is the sum of: GWP-fossil; GWP-biogenic; GWP-luluc.

Moreover, with the aim to go a step further as highly suggested by Level(s) for avoiding burden shifting, nine other environmental indicators (Table 6) in addition to GWP are evaluated into the Life cycle cloud-based platform.

Impact category	**Indicator**	**Unit**
Ozone Depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC 11 eq. /m^2
Acidification	Acidification potential, Accumulated Exceedance (AP)	mol H+ eq. /m^2
Eutrophication aquatic freshwater	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-freshwater)	kg PO4 eq. /m^2
Eutrophication aquatic marine	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-marine)	kg N eq. /m^2
Eutrophication terrestrial	Eutrophication potential, Accumulated Exceedance (EP-terrestrial)	mol N eq. /m^2
Photochemical ozone formation	Formation potential of tropospheric ozone (POCP)	kg NMVOC eq. /m^2
Depletion of abiotic resources - fossil fuels	Abiotic depletion potential (ADP-fossil) for fossil resources	MJ/m^2, net calorific value
Depletion of abiotic resources - minerals and metals	Abiotic depletion potential (ADP-minerals&metals) for non-fossil resources	kg Sb eq. /m^2
Water use	Water (user) deprivation potential, deprivation-weighted water consumption (WDP)	m^3 world eq. deprived/m^2

Table 6. LCA environmental indicators

The main reference standard providing the calculation method is EN 15978 *"Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method"* and EN 15804 "*Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products"* for the assessment of whole environmental performance at building level and product level respectively. Reference is also made to ISO 14040 *"Environmental management - Life cycle assessment - Principles and framework"*, ISO 14044 *"Environmental management - Life cycle assessment - Requirements and guidelines"* and PEF "Product Environmental Footprint".

4.2.6 LCA software and database

As calculation tool for assessing GWP and additional indicators, SimaPro 9.6.0.1 software and Ecoinvent 3.10 database were adopted. An overview of their distinguishing features is reported in Table 7 according to the Level(s) criteria about three key aspects (typically addressed in varying degrees by the LCA tools available on the market):

- *Comprehensiveness*: whether the tools are specific for construction, the building elements they cover, the life cycle stages they cover and the indicators for which they calculate results.
- *Robustness*: the extent to which the calculation rules are aligned with EN 15978/15804, how data quality is accounted for and transparency in reporting data sources and assumptions.
- *Operability*: accessibility of the software to users, interoperability with other software, the cost and available training and support.

Parameter	**SimaPro software**	**Ecoinvent database**
A. Comprehensiveness		
A1) Construction-specificity	II) Broader scope, including a wide range of industrial sectors among which construction	II) Broader scope, including a wide range of industrial sectors among which construction
A2) System boundaries & scope	EN 15978 modules covered A1-A3: Product stage (material extraction and processing, transport, manufacturing)	EN 15978 modules covered A1-A3: Product stage (material extraction and processing, transport, manufacturing)

	A4-A5: Construction process stage (transport to the building site and installation) B1-B5: Use stage – building fabric (maintenance, repair, replacement, refurbishment) B6-B7: Use stage - operation of the building (operational energy and water use) C1-C4: End-of-life stage (de-construction & demolition, transport, waste processing for reuse, recovery and/or recycling, disposal) D: Benefits and loads beyond the system boundary *Extra:* Separate reporting: Yes Databases used: many options Languages available: many options, including English, European and extra-EU languages	A4-A5: Construction process stage (transport to the building site and installation) B1-B5: Use stage – building fabric (maintenance, repair, replacement, refurbishment) B6-B7: Use stage - operation of the building (operational energy and water use) C1-C4: End-of-life stage (de-construction & demolition, transport, waste processing for reuse, recovery and/or recycling, disposal) D: Benefits and loads beyond the system boundary *Extra:* Separate reporting: Yes Countries covered: many options, including all European member states and many extra-EU countries Languages available: many options
A3) Indicators	I) Full coverage of indicators set in EN 15978:2011 + additional PEF indicators	I) Full coverage of indicators set in EN 15804:2012+A2:2019
A4) Modelling granularity	a) Specific parts of the building (assessment at the most detailed degree)	a) Building material (assessment at the most detailed degree)
B. Robustness		
B1) Methodological adherence to Levels and EN standards	I) Aligned with EN 15978 with extension to fit with Level(s)	I) Aligned with EN 15804 with extension to fit with Level(s) *Extra:* EN 15804:2012+A1:2013 and EN 15804:2012+A2:2019
B2) Data quality	The tool supports: a) Reliability assessment of the quality of the data input	The database provides/enables data quality assessment for the following aspects: a) Geographical representativeness (e.g., local vs. EU/global average)

	b) Sensitivity analysis (e.g., check influence of parameters and datasets on results) c) Uncertainty analysis (e.g., check variability of results) d) Scenario analysis (e.g., check of alternative options)	b) Time-related representativeness (e.g., plausible until a certain year) c) Technological representativeness (e.g., material-specific vs. generic) d) Uncertainty analysis is supported (e.g., uncertainty distributions provided) *Extra:* Datasets can be adapted depending on needs
B3) Transparency and verification	I) Sources of information, key data and modelling assumptions are trackable and verifiable, and documented in detail inside the software (data available and accessible at unit process level) *Extra:* The software is constantly updated	I) Sources of information, key data and modelling assumptions are trackable and verifiable, and documented in detail (data available and accessible at unit process level) *Extra:* The database is updated yearly with expanded sectorial and geographical coverage, after independent review procedure, verification and validation
C. Operability		
C1) Accessibility	a) Web interface c) Software to install on a computer/server	a) Datasets provided at the detail level of unit processes
C2) Data exchange & interoperability	III) Import/export of LCA information possible in specific format (e.g., xls, ILCD)	II) Import/export possible based on fee
C3) Cost	II) Available at a commercial price	II) Available at a commercial price
C4) Training and support	a) Demo version, documentation and/or initial training available for free b) Long distance learning offered c) After sale support offered (e.g., helpdesk)	a) Demo version, documentation, and/or initial training available for free b) Long distance learning offered c) After care support offered (e.g., helpdesk)
D. Additional information	Software developed by PRé Sustainability, starting from 1990	International database founded by the Swiss research institutions ETH, EPFL, Empa, Agroscope and the Paul Scherrer Institute in

		2003 and containing more than 20.000 reliable life cycle inventory datasets

Table 7. Distinguishing features of SimaPro 9.6.0.1 and Ecoinvent 3.10

In overall terms, it is possible to state that the selected software and database allow to support science-based environmental assessments and provide high-quality LCA analysis for empowering informed decision-making during the whole building process, starting from the early design. Nonetheless, it is worth highlighting that SimaPro is intended for LCA expert end-users. Not being conceived for design professionals, the software does not ensure interoperability with the commonly used design tool, namely CAD and BIM, and shows limits in the import of new material EPDs. To fill this gap, an Excel worksheet is used to integrate the LCA impacts resulted from SimaPro and the LCA impacts retrieved from Environmental Product Declarations (for more details, see "LCA data quality").

4.2.7 LCA data quality

Since the degree of confidence placed in the LCA results of an assessment depend upon the level of precision and detail provided by the data and the information used to model the building being assessed, special effort has been made into the data collection, in collaboration with all RE-SKIN partners. In particular, the data at issues are related to:

- *Foreground processes*, which directly affect the results (e.g., the actual content of steel in a building component, the consumption of electricity during the occupation of a building)
- *Background processes*, which are linked to and are nested behind the foreground processes (e.g., the production and supply of steel, the production and supply of grid electricity).

For the quantification of data for both foreground and background processes, priority is given to the following sources, listed in in hierarchical order and used in practice individually or in combination:

- *Primary data*, namely site-specific information based on direct measurements or the characterisation of parameters for a certain context;
- *Secondary data*, available from technical literature and data providers (e.g., specific studies, LCA databases);
- *Assumptions*, worst case applied when satisfactory data is not available.

Specifically, the present Life cycle cloud-based platform uses:

- Specific data derived from specific production processes. This occurs for all components supplied by the RE-SKIN partners, with whom an intensive collaboration has been launched to find and refine as much as possible the data underlying the assessment, for improving the related granularity and representativeness. Where available, the product-specific Environmental Product Declarations (EPDs) describing RE-SKIN components and thus calculated using specific data are directly included for accounting the specific environmental impacts of each life-cycle stage.
- Average data derived from specific production processes. In the event of building components supplied by third parties (non-RE-SKIN partners), the selection of Ecoinvent datasets has been prioritized to take advantage of transparent and comprehensive inventory. In absence of datasets, the EPDs describing the same products but not RE-SKIN specific is accounted as representative of the environmental profile.

To make evidence of the high-quality data of the overall rating, the Data Quality Index (DQI) defined by Level(s) will be calculated for each hotspot of the environmental impacts identified from the life-cycle GWP, as appropriate, related to building life cycle stages or modules, components, elementary flow, or combinations thereof.

Table 8 shows for which technological parts specific LCA studies has been developed within the RE-SKIN project (RE-SKIN LCA study) or, alternatively, where LCA impacts are retrieved directly from EPDs (product-specific / no product-specific) or using a dataset of Ecoinvent database, modelled in SimaPro to obtain the impact assessment results (SimaPro).

Building parts	Technological solution	LCA impacts source	LCA data quality
Shell (substructure and superstructure)			
Facades wall	Multifunctional prefabricated façade system	RE-SKIN LCA study for BioPUR foam EPD product-specific for GreenCoat steel RE-SKIN LCA study for Aluminium substructure	Primary data from Indresmat, SSAB and Garcia Rama (RE-SKIN partners)
Façade openings	Low-e film	EPD no product-specific	Secondary data from Saint-Gobain*

	Sun control film	EPD no product-specific	Secondary data from 3M*
	New window with PVC frame and double glazing	SimaPro	Secondary data from Ecoinvent database
Roof	Building-integrated photovoltaic-thermal (BIPVT) system	RE-SKIN LCA study for BioPUR foam EPD product-specific for GreenCoat steel RE-SKIN LCA study for Aluminium substructure	Primary data from Indresmat, SSAB and Garcia Rama (RE-SKIN partners)
Core (fittings, furnishings and services)			
Energy system	DC heat pump	RE-SKIN LCA study	Primary data from Heliotherm (RE-SKIN partner)
	Smart fan-coils	RE-SKIN LCA study	Primary data from Stille (RE-SKIN partner)
	Refurbished PV modules	RE-SKIN LCA study	- waiting for NDA -
	Multi-input/multi-output (MIMO) converter	RE-SKIN LCA study	Primary data from Power Smart Control (RE-SKIN partner)
	Repurposed battery system	RE-SKIN LCA study	Primary data from Solartechno (RE-SKIN partner)
External works			
Utilities	Electric Vehicles (EV) charger	EPDs product-specific for: Waybox cable Waybox socket JuicePole Single/Three-phase JuicePole Three/Three-phase	Primary data from Enel-X (RE-SKIN partner)

Table 8. LCA studies sources for building and technological part

* Company not involved into the project, unlike other producers that are RE-SKIN partners.

4.2.8 LCA platform user inputs

In spite of a large amount of data is needed to carry out an LCA study at building level, due to the involvement of industrial partners, most of them, such as materials, energy consumption, emissions, waste generation, transportation logistics, lifetime and end of life scenarios, turns out to be pre-set for each RE-SKIN component into the Life cycle cloud-based platform. In this way, the aim is to limit data entry by the users for running LCA of retrofit buildings, with a twofold purpose:

- Simplification: Easing the input process makes the platform more user-friendly, reducing the potential for user errors and making it accessible to a wider range of users, including those with less experience in LCA;
- Usability: By limiting inputs to essential and relevant data, the platform helps users focus on what is necessary, avoiding the confusion that can come with an overwhelming number of input fields and providing scientific advice to inform the decision-making process.

The LCA platform user inputs as shown in Table 9, by reporting separately what is required in general at the building level and in particular for the different building parts.

Building	**Description**	**User inputs**
Shell (substructure and superstructure)		
Building area	Useful internal floor area	m^2 of useful internal floor area
Building energy consumption	Operational energy for heating, cooling and Domestic Hot Water (DHW)	kWh of operational energy
Facades wall	Multifunctional prefabricated façade system	m^2 of external wall systems
Façade openings	Low-e film Sun control film New window with PVC frame and double glazing	m^2 of windows (where needed, split according to the selected retrofit solutions)
Roof	Building-integrated photovoltaic-thermal (BIPVT) system	m^2 of roofing systems
Core (fittings, furnishings and services)		

Energy system	DC heat pump	number of items
	Smart fan-coils	number of items
	Refurbished PV modules	number of items
	Multi-input/multi-output (MIMO) converter	number of items
	Repurposed battery system	number of items
External works		
Utilities	Electric Vehicles (EV) charger	number of items (where needed, split according to the selected charging solutions)

Table 9. LCA platform user inputs

As optional function, users can adjust the transport, preliminarily established into the life cycle cloud-based platform by georeferencing the construction site in question (location as user input data) and by the automatic calculation to the different manufacturing plants of RE-SKIN components (locations from industrial partners). Indeed, in the event of change in the involved producers, it is possible to directly entering the distances covered by the different means of transport, to enable more extensive assessments (Table 10).

Transport	**Transport solutions**	**User inputs**
via Road	Lorry EURO5	tonnes of transported cargo (ton) kilometres travelled (km)
	Lorry EURO6	ton and km (as above)
via Rail	Train diesel	ton and km (as above)
	Train electricity	ton and km (as above)
via Water	Inland waterways barge	ton and km (as above)
	Container ship	ton and km (as above)

via Air	Aircraft very short haul	ton and km (as above)
	Aircraft short haul	ton and km (as above)
	Aircraft medium haul	ton and km (as above)
	Aircraft long haul	ton and km (as above)

Table 10. LCA platform user inputs for transport

4.2.9 LCA platform application

With reference to the stages of the project defined by Level(s), the LCA platform application is intended for detailed design and construction (Level 2) and as-built and in-use (Level 3). Conceptual design (Level 1) is mostly neglected since is related to the reviewing of the design principles that contribute most to the environmental impacts (e.g., GHG emissions) along the building life cycle. Instead of focusing on literature studies, the following stages draw attention on the building:

- Level 2 - Detailed design and construction: it is based on calculations, simulations and drawings. The environmental impacts associated with a building design and each life cycle stage are modelled and measured, allowing the evaluation of different design scenarios and future life cycle scenarios;
- Level 3 - As-built and in-use: it is based on commissioning, testing and metering. The building materials used and assumptions made in order to calculate the environmental impacts are validated against the as-built information as it becomes available.

Note that the same LCA procedure and instructions as defined for Level 2 are equally applied to the building assessment after renovation, namely at Level 3. The only difference is that building data is supported by the certainty of materials procured and technical building components installed instead of being based on a design only.

4.3. Circular Economy

Despite the large number of contributions on the topic of circularity assessment, there are currently several tools and frameworks that are still not standardized and difficult to interpret for stakeholders in the construction sector. In order to choose the most appropriate indicators for orienting and assessing circularity within RE-SKIN project, the present section proposes a dynamic tool that collects, clusters, compares and select the main Circularity KPIs (CKPIs) extracted from both voluntary references (standards and frameworks developed by standardization bodies, scholars, research centers, construction firms, etc.) and mandatory references (i.e., European and international regulatory framework).

Drawing on insights from a range of existing literature and tools, the work aimed at integrating different perspectives and addresses the basic needs of a standardized approach to circularity analysis. Starting from the state of the art on performance indicators in the construction industry, an innovative scalable framework has been developed for the selection of circularity indicators applicable at different scales of the RE-SKIN project, i.e., product, project, building, process, organization. The framework seeks to reconcile existing asymmetries and redundancies in CKPIs and criteria of assessment, creating a common platform for RE-SKIN project members and stakeholders to manage the complexity of circularity.

In particular, the work has firstly examined the broad spectrum of references at the international level, characterized by significant complexity and diversity in the collection of indicators. These references span multiple categories, that can be grouped into the following three categories (Table 11):

- regulations and directives;
- technical standards and voluntary guidelines;
- ranking systems and certification schemes.

References containing qualitative and quantitative indicators of circularity	
Regulations and Directives	• *Regulation (EU) 2022/1288* • *SWD (2016) 180 final - EU Green Public Procurement (GPP) for Office Building Design, Construction and Management* • *SWD (2017) 283 final - EU Green Public Procurement (GPP) for Furniture* • *Regulation (EU) 2020/852 - EU TAXONOMY based on Do Not Significant Harm (DNSH)* • *European Sustainability Reporting Standards (ESRS) Exposure Drafts by European Financial Reporting Advisory Group (EFRAG)* • *EU Green Bond Standard (GBS).*
Standards and Voluntary Guidelines	• *ISO 20887:2020 - Sustainability in buildings and civil engineering works. Design for disassembly and adaptability* • *ISO 59020 - Circular economy. Measuring and assessing circularity* • *EN 17902 - Furniture. Circularity. Requirement and evaluation methods for dis-/reassembly* • *Level(s)* • *Green Building Index (GBI) Assessment Criteria for Non-Residential New Construction (NRNC) 1.0 and Residential New Construction (RNC) 3.0* • *Regulatory Technical Standards (RTS) by European Securities and Markets Authority (ESMA)* • *International Integrated Reporting Council (IIRC) by International Financial Reporting Standards (IFRS) Foundation* • *Global Reporting Initiative (GRI)* • *UNI/TS 11820:2022 – Measuring circularity. Methods and indicators for measuring circular processes in organizations*
Ranking System and Certifications	• *Deutsche Gesellschaft für Nachhaltiges Bauer (DGNB) Checklists – German Sustainable Building Council* • *Ellen MacArthur Foundation (EMF) - Material Circularity Indicator (MCI)* • *Global Real Estate Sustainability Benchmark (GRESB) Assessment* • *Circular Transition Indicators (CTI) by World Business Council For Sustainable Development (WBCSD) 4.0* • *Building Research Establishment Environmental Assessment Methodology (BREEAM) Certification - UK New Construction Technical Manual 6.1* • *Sustainability Accounting Standards Board (SASB) by International Financial Reporting Standards (IFRS) Foundation* • *Leadership in Energy and Environmental Design (LEED) Certification 4.1 – Building Design + Construction / Interior Design + Construction / Operations + Maintenance* • *ARUP Circular Buildings Toolkit* • *WELL Building Standard Certification 2.0 [2023]* • *National Green Building Standard (NGBS) Certification [2020]*

Table 11. Circularity references' categories

In the pursuit of a well-structured and comprehensive framework, the organization of data and information plays a pivotal role. Hence, the identified Circularity KPIs have been analysed, examined and classified in a framework according to: aims, topic, scale, type of assessment (quantitative, qualitative or mixed), formulation (binary yes/no selection, open question or suggestion), life cycle stages, classification purpose (as-is or attitude), sustainability principles (among re-use, re-cycle or prevention).

The first screening of circularity indicators counted about 60 CKPIs (Shown in the Annex). The analysis and comparison of the indicators, extracted from the various sources highlight redundancies and the recurrence of some topics that appear to be priorities for most references. The comparison of these 60 indicators allows to investigate the areas of major interest and the most shared approaches in assessing circularity (Figs. 2-5).

In particular with reference to the total of 60 indicators, figure 2 shows the percentages of indicator per category of scope or scale, according to the following categories: products and materials, buildings, organization. Precisely:

- **Products and Materials Level**. At this level, Circularity KPIs pertain to the evaluation of individual products, materials and components used in construction. This includes technical elements, furniture, and considerations related to energy efficiency within these elements. Indicators at this scale focus on the sustainable sourcing, use and disposal of construction elements.
- **Building Level**. Circular construction principles are applied at the building level, encompassing entire construction projects. Indicators operating at this scale evaluate the circularity of entire buildings, including their design, construction, operation, and potential reuse or deconstruction. These indicators offer insights into the overall sustainability and circularity of construction projects.
- **Organization Level**. The organization level of Circularity KPIs extends beyond the physical aspects of construction and delves into organizational and economic aspects. These indicators assess the practices and policies of construction companies and organizations, examining how they integrate circularity principles into their strategies, supply chain management and financial decision-making. This level also considers broader economic implications and benefits associated with circular construction practices.

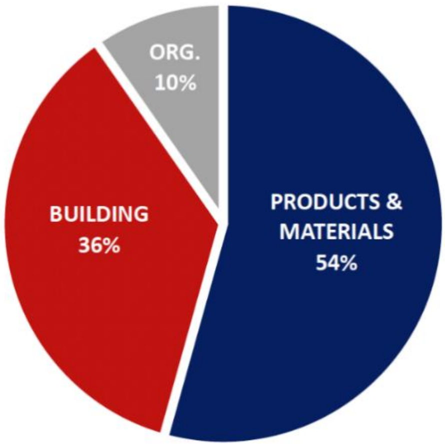

Figure 2. Percentages of analysed indicators per category of scope or scale

The results of the analysis show that more than half of the analysed indicators refers to the products and materials level, followed by the building level (the suitable one for the RE-SKIN sustainability assessment tool).

With reference to the total of 60 indicators, figure 3 shows the percentages of indicator per "Type of Assessment" according to the following articulation:

- **quantitative**: indicators that involve numerical data and measurements (e.g., formula with threshold, quantitative metric, etc.);
- **qualitative**: indicators that do not rely on numerical values but instead provide qualitative assessments (e.g., binary selection, open question, suggestion, etc.);
- **mixed**: indicators that encompass both quantitative and qualitative aspects.

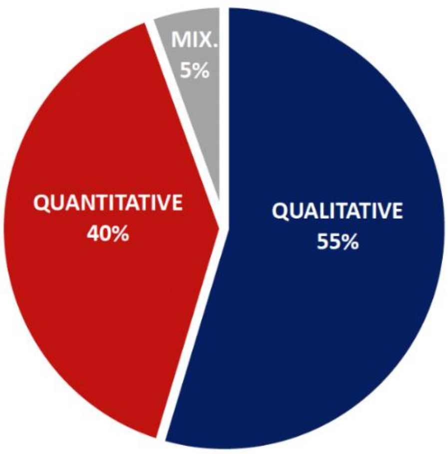

Figure 3. Percentages of analysed indicators per assessment type

With reference to the total of 60 indicators, figure 4 highlights the articulation of indicators according to the addressed circular strategy. In particular, the classification proposed – namely: "re-use", "re-cycle" and "prevention" – is derived from United Nations Environment Programme (UNEP) articulations of the key strategies in the field of circular economy. Specifically:

- **Re-use**. This principle involves extending the lifespan of products or materials by using them again for their original purpose or a similar one without significant processing.
- **Re-cycle**. Recycling focuses on breaking down materials or products into their raw materials and using these materials to create new products, reducing the need for virgin resources.
- **Prevention**. Prevention strategies aim to reduce waste generation and environmental impact by minimizing the consumption of resources and the creation of waste in the first place.

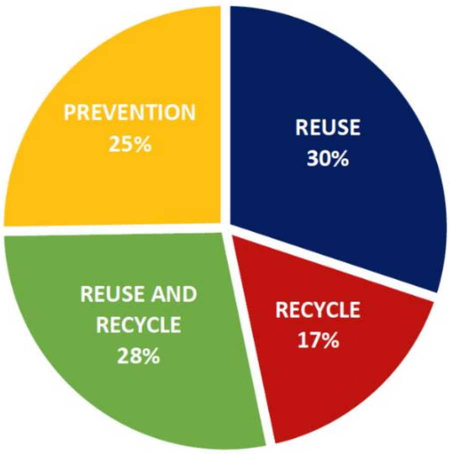

Figure 4. Percentages of analysed indicators per category of strategy

The results show how the indicators cover the three circular strategies non homogeneously, with a preference for reuse followed by recycle.

Figure 5 describes the analysed indicators according to "As-Is" and "Attitude" categories, which refer to the current state of circularity ("As-Is") and the prevailing attitude towards circular economy principles ("Attitude"). In particular:

- **As-Is**: these indicators refer to the current state of circularity of a system. These indicators provide a snapshot of how circular practices are currently being implemented or the extent to which resources are being conserved and waste is being minimized. As-is circular indicators can measure various aspects, such as the content of recycled or reused matter of a product, the lifespan of products, etc.

- **Attitude**: these indicators assess the level of potential, willingness, intention, improvement, awareness, and commitment of a system (building, component, materials, etc.) in adopting or continuing with circular practices in the future. They can measure for instance the capability of a building to be expanded in the future or the content of recyclable or reusable matter of a product, etc.

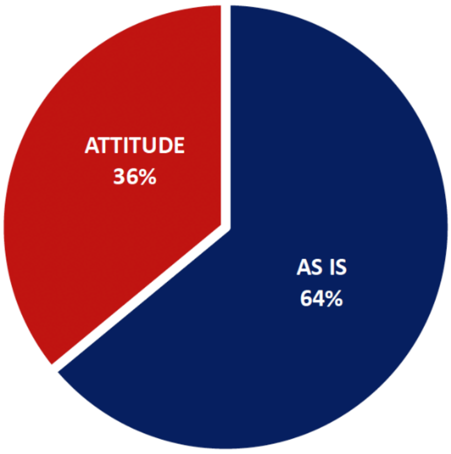

Figure 5. Percentages of analysed indicators per purpose: "as-is" and "attitude"

It is possible to observe in figure 5 how the majority of indicators refer to the "as is", thus focusing on the current state of the system rather than its future circular potential.

The results of the analyses in Figs. 2-5 have also allowed to propose a Short List (Table 12) selecting from the extended list of Circularity KPIs the most significant indicators with respect to the suitability with ENELX assessment tool and in alignment with the objectives of RE-SKIN Task 7.1.

The Circularity KPIs Short List includes indicators that align with the requirements of the assessment framework and the calculation software developed by ENELX. Table 12 shows the 19 selected circular KPIs suitable for RE-SKIN project. For further details please refer to "Annex 7 - Building Circularity KPIs table – extended version".

#	Indicator	Description
S.1	Resource inflows: renewable products and materials	The weight in both absolute value and percentage of renewable input materials from regenerative sources used to manufacture the undertaking's products and services (including packaging)
S.2	Resource inflows: reused products and materials	The weight in both absolute value and percentage, of reused or recycled products and materials (= non-virgin) used to manufacture the undertaking's products and services (including packaging).
S.3	Resource inflows: recycled products and materials	The weight in both absolute value and percentage, of reused or recycled products and materials (= non-virgin) used to manufacture the undertaking's products and services (including packaging).
S.4	Resource inflows: remanufactured/repurposed/reconditioned products and materials	The weight in both absolute value and percentage, of remanufactured/repurposed/reconditioned products and materials (= non-virgin) used to manufacture the undertaking's products and services (including packaging).
S.5	Virgin raw materials	% of virgin raw materials
S.6	Recyclable content	% of recyclable content
S.7	Reusable content	% of reusable content
S.8	Waste at disposal	% of waste generated for the manufacturing and installation of RE-SKIN system that is sent at disposal

S.9	Resource outflows: waste to recovery	The manufacturer shall disclose in tonnes or kilogrammes: for each type of hazardous and non-hazardous waste, the percentage of waste diverted from disposal by recovery operation type and the total amount summing all three types. The recovery operation types to be reported on are: i. preparation for reuse; ii. recycling; and iii. other recovery operations;
S.10	Outline Waste Management Plan (WMP)	Presence of WMP to explain (i) how environmental and health impacts from CDW can be reduced; (ii) how cost benefits can be maximised (i.e., increased revenues and avoided costs) and (iii) how the segregated collection of onsite waste can be optimised based on the different possible end market, storage, processing and disposal options.
S.11	Elements and their parts independent and easily separable	The potential to separate building elements that are connected to each other and to disassemble elements into their constituent components and parts.
S.12	Connections mechanical and reversible	The use of mechanical, non-destructive connections as opposed to chemical bonding.
S.13	Connections easily accessible and sequentially reversible	Easy and sequential access in order to reverse mechanical connections and remove elements, components or parts.
S.14	Specification of elements and parts using standardised dimensions	Specification of elements and parts of a standardised specification in order to provide consistent future stock.
S.15	Specification of modular building services	Specification of modular systems that may retain value upon de-installation or which may be more easily swapped out and upgraded.
S.16	Parts made of homogenous materials with minimal unnecessary treatments or finishes	Specification of components and constituent parts made of homogenous materials, the same materials or materials mutually compatible with recycling processes. N.B. Finishes, coatings, adhesives or additives should not inhibit recycling.
S.17	Established recycling options for constituent parts or materials	The part or material is readily recyclable into products with a similar field of application and function, thereby maximising their circular value.

S.18	Reusability	Practically reusable or not — for a product to be deemed reusable, there needs to be an application that allows an end-user to economically reuse the product without extensive cleaning or restoration; Reuse can be graded on a continuum, ranging from reuse of the entire structure to reuse of selected materials.
S.19	Comparison of lifetimes and sequence of possible renovation measures	Have the service life of the building materials applied been coordinated so that no intact building materials or components have to be damaged in future renovation measures?

Table 12. Building Circularity KPIs selected for RE-SKIN project

From the Short List of circularity KPIs (Table 12), a refinement work has been performed together with Enel X in order to develop a simplified section for the circularity assessment to be combined with the "energy" and "LCA" evaluation sections of the whole assessment framework. This work has been developed by step-by-step dialogue between POLIMI and ENELX.

The results of this further simplification is the list of circularity indicators, i.e., Circularity Checklist, shown in Table 13. In the last column of table, it is possible to trace the reference to the Circularity KPIs in Table 12.

Indicators	**Description**	**UoM**	**Reference to Table 12 KPIs**
Building			
Sustainable design			
Presence of environmental labels	Presence of environmental labels (e.g., LEED, BREEAM, others)	Yes/No	
Compliance with standards	Reference to EU GPP criteria/CAM	Yes/No	
	Reference to other standards (e.g., EU Taxonomy, Steel produced in compliance with Sustainable Steel Principles)	Yes/No	
Environmental studies	Presence of environmental studies (e.g., LCA, carbon footprint)	Yes/No	
Sustainable inputs			

Building materials origin ***Composition relative to a single material weight***	Share of virgin material	% (w/w)	S.5
	Share of recycled material	% (w/w)	S.3
	Share of reused material	% (w/w)	S.2
	Share of refurbished material	% (w/w)	S.4
Intervention materials composition	Share of biobased materials	% (w/w)	S.1
	Share of non-biobased materials	% (w/w)	
Sharing			
Space-sharing design	Multi-purpose spaces	Yes/No	
Reuse and recycle			
Waste produced	Share of waste to landfill	% (w/w)	
	Share of waste to recovery	% (w/w)	
	Share of waste to recycle	% (w/w)	
	Share of waste to reuse	% (w/w)	
	Share of waste to refurbishment	% (w/w)	
Intervention - Construction site and RE-SKIN package-related			
Sustainable design			
Presence of environmental labels	Presence of environmental labels (e.g., LEED, EPD, others)	Yes/No	
Compliance with standards	Reference to EU GPP criteria/CAM	Yes/No	
	Reference to other standards (e.g., EU Taxonomy, Steel produced in compliance with Sustainable Steel Principles)	Yes/No	S.10, S.11, S.12, S.13, S.14, S.15, S.17, S.18, S.19

Environmental studies	Presence of environmental studies (e.g., LCA, carbon footprint)	Yes/No	
Sustainable inputs			
Building materials origin Composition relative to a single material weight	Share of virgin material	% (w/w)	S.5
	Share of recycled material	% (w/w)	S.3
	Share of reused material	% (w/w)	S.2
	Share of refurbished material	% (w/w)	S.4
Building materials features (attitude)	Recyclable content		S.6
	Reusable content		S.7
Building materials composition	Share of biobased material	% (w/w)	S.1
	Share of non-biobased material	% (w/w)	
Building materials design	Design for end-of-life extension *Designed-for-reuse/recycle/refurbishment materials*	Yes/No	S.19
	Design for easy maintenance during life cycle *Designed-for-disassembly materials*	Yes/No	
Reuse and recycle			
Waste produced	Share of waste to landfill	% (w/w)	S.8
	Share of waste to recovery	% (w/w)	S.9
	Share of waste to recycle	% (w/w)	S.9
	Share of waste to reuse	% (w/w)	S.9
	Share of waste to refurbishment	% (w/w)	S.9

Table 13. Building Circularity Checklist – Circular Economy indicators developed by POLIMI and ENELX

It is important to highlight that this is an ongoing work and that the Circularity Checklist agreed by POLIMI and ENELX is still a work in progress. Below some comments and still open-issues related to the Circularity Checklist are reported:

- the section of indicators on the reuse and recycling of the EX-ANTE building should be reviewed and modified. For the existing building, it is possible to assess what definitely shall go to landfill (because no recovery can be performed) and what is recoverable; the further articulations on refurbishment, recycled, reused, etc. are not realistic because the more detailed circular processes depend on the context of the building (e.g., if in the area of the building site there are no processing plants able to refurbish the dismantled elements, refurbishment cannot be applied as circular strategy);
- it is important to clearly define "when" the indicators shall be calculated, e.g., in which stage of the building process? Design, construction, maintenance, renovation, demolition, recovery, etc.? Each indicator can (or cannot) be calculated at a specific stage of the building process (with different efforts in collecting the information needed to calculate the indicator);
- the Circularity KPIs listed in Table 12 can be considered the most simplified level for the assessment of circularity, in alignment with the ENELX tool. For further implementations of the tools or for more detailed investigations about the circularity of alternative solutions/strategies, it is possible to integrate the assessment of the tool with the application of other Circularity KPIs extracted from both the extended and the short lists.

5. RESULTS REPRESENTATION

The goal is to obtain a single indicator (In CO_{2eq}) that quantifies sustainability, taking into account operational and embodied energy (also maintenance and component disposal cycles). In order to have a whole overview of the building performance, not only related to the GWP indicator, the set of indicators abovementioned will be also shown.

The results will be presented in three aspects: energy, LCA, circularity.

5.1. Output and interpretation

Because the model is complex, and there is a large number of possible solutions (in terms of technologies and specifications for each technology), the strategy is to calculate the model for each possible setup, those could be several thousands.

Graphically the result is a cloud of points.

From this cloud we can compute what is called an pareto frontier, that is, a set of the most external points of the cloud. These points have the property of being the maximum value for a specific value of the other variable: for example, for a chosen Global Cost, we can find the minimum embodied CO_2 eq, or for a chosen CO_2 eq Emission, we can find the least expensive setup of technologies.

The list of potential charts available in the platform, are shown hereafter.

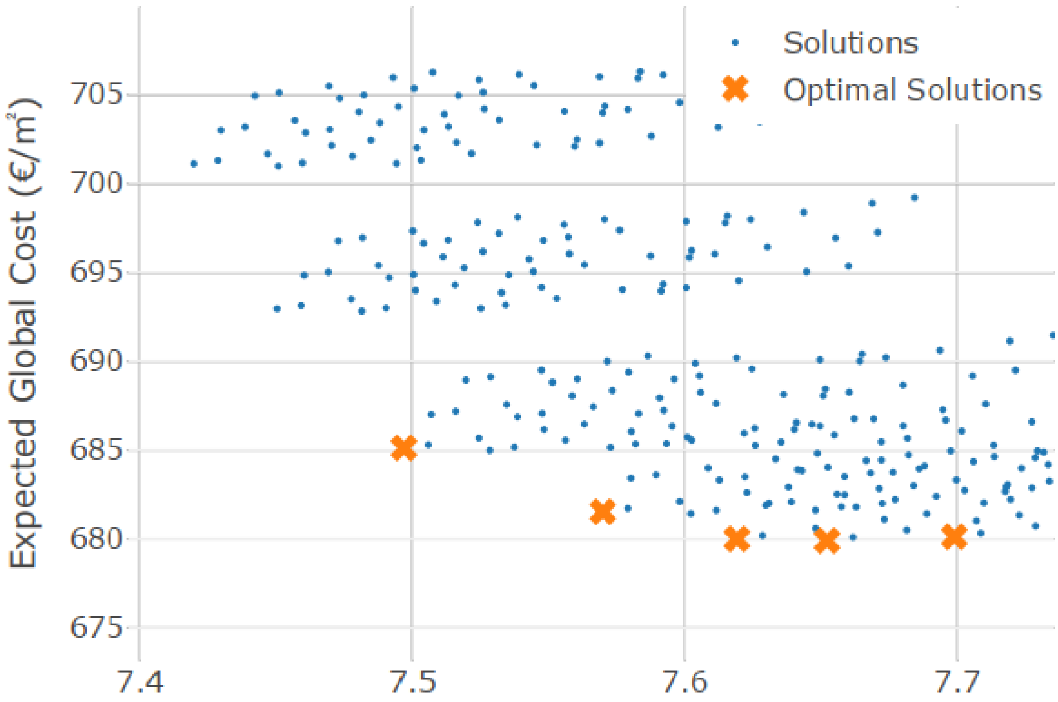

Figure 6. Yearly CO_2 Emission (Operational) (kg/m^2)

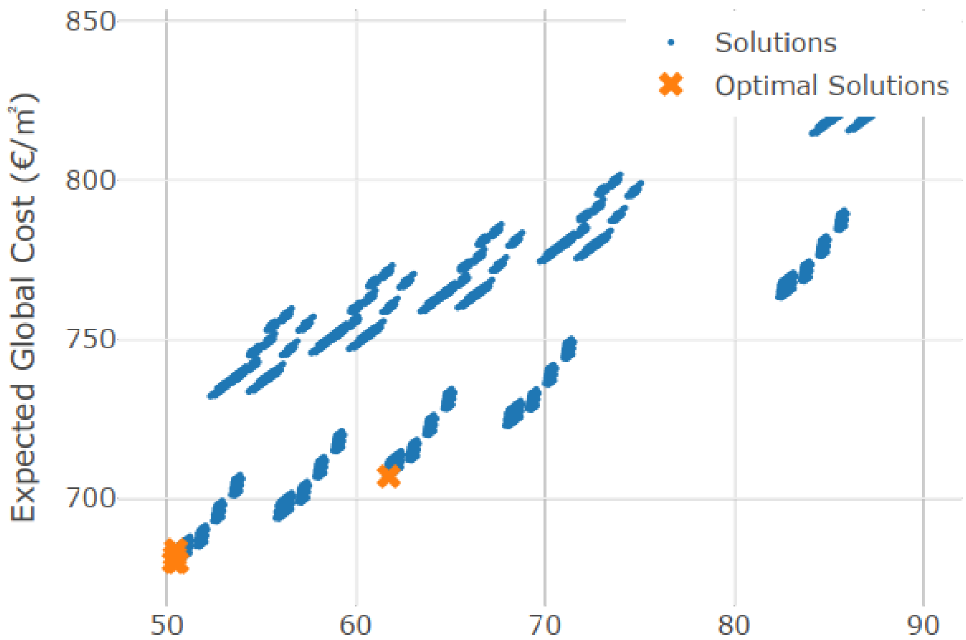

Figure 7. Yearly Primary Energy Consumption Operational and Embodied (kWh/m^2)

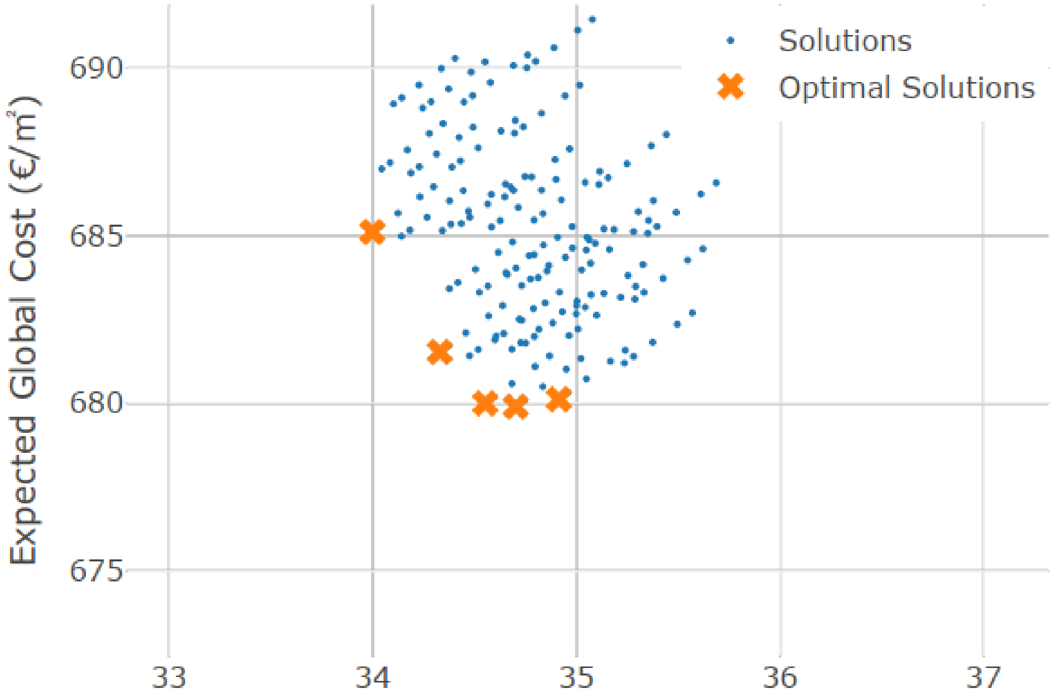

Figure 8. Yearly Primary Energy (Operational) (KWh/m²)

5.2. Energy related output

Regarding the energy analysis, there are two main outputs: Building total energy consumption and Building consumption distribution by energy carrier.
In the following, the graphical representation of the main outputs are described.

1. Building total energy consumption Pre and Post-intervention in kWh/m^2, split by thermal energy and electrical energy. Figure 9 reports the first of the two main quantitative indicators of the "Energy consumption" area.

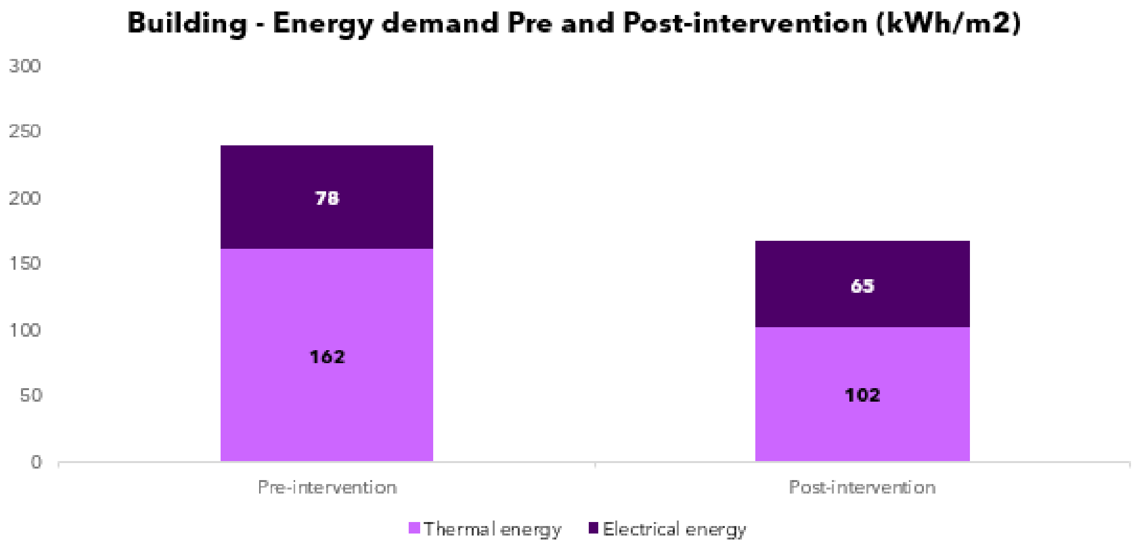

Figure 9. Example of "Building - Energy demand Pre and Post-intervention (kWh/m²)" chart

2. Building consumption distribution by energy carrier Pre-intervention in %. Figure 10 shows the ratio between total electrical and thermal consumption "as-is".

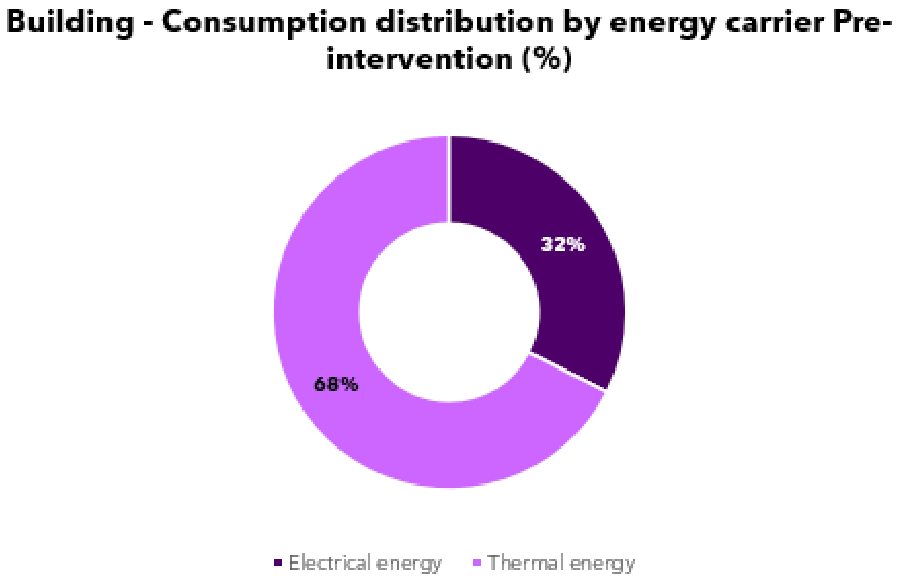

Figure 10. Example of "Building - Consumption distribution by energy carrier Pre-intervention (%)" chart

3. Building consumption distribution by energy carrier Post-intervention in %. Figure 11 displays the ratio between total electrical and thermal consumption after the implementation of RE-SKIN solutions.

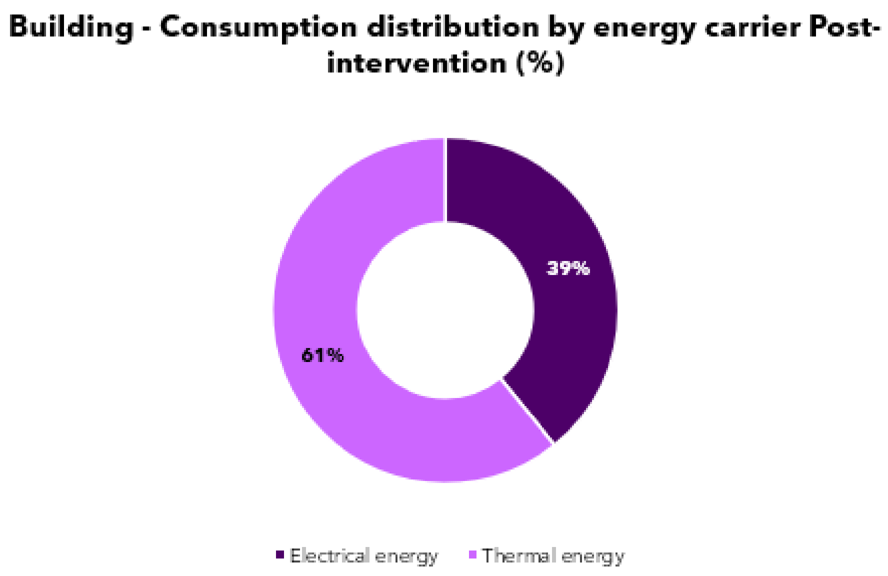

Figure 11. Example of "Building - Consumption distribution by energy carrier Post-intervention (%)" chart

5.3. LCA related output

By taking Global Warming Potential (GWP) as key indicator, the main unit of measurement displayed in the Life cycle cloud-based platform is $kgCO_2eq$ per m^2 useful internal floor area for a reference study period of 50 years. As required by the LCA standards and Level(s), results are reported for each life cycle stage included within the system boundary, in the form presented for GWP (Table 14) but also provided for all other additional indicators.

Indicator	Unit	Product (A1-A3)	Construction (A4-A5)	Use stage (B1-B6)	End of life (C1-C4)	Benefits and loads (D)
GWP - total	$kgCO_2eq$					
GWP - fossil	$kgCO_2eq$					
GWP - biogenic	$kgCO_2eq$					
GWP - land use and land use change	$kgCO_2eq$					
Notes: Impacts referred to the use of 1 m^2 of useful internal floor per year for a default reference study period of 50 years.						

Table 14. List of GWP indicators and their units of measurement

In this way, LCA results focus on GWP at building level, but with the chance to look in detail all environmental indicators, with related hotspot analysis to identify areas of improvements and further details at component level. This is crucial to provide insights of the environmental profile of the RE-SKIN components included into the retrofit toolkit. The whole life cycle impacts are displayed both in tabular form (Table 14) and in graphical form (Figure 12) for making data more accessible, understandable and actionable. While numerical values are displayed for all indicators, it is currently investigated to focus the charts only for GWP or, alternatively, also for all additional environmental indicators. In the first case, it is possible to express directly the characterized impacts in terms of $kgCO_2eq$, whereas in the second case, since indicators are expressed into different units, impacts have to be normalized to appear as percentage (Figure 12).

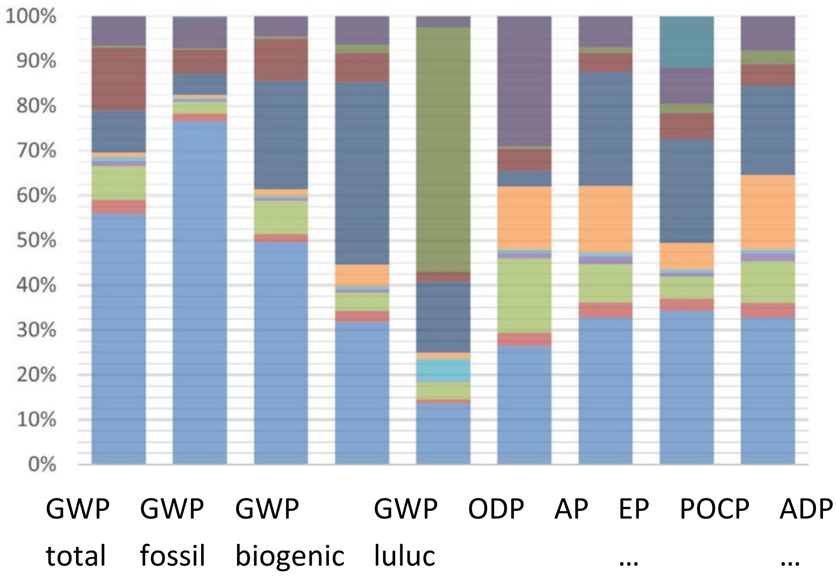

Figure 12. Representation of normalized impacts, expressed as percentage

In the tables and graphs, it is possible to read the contribution related to different aspects: the life cycle stages, modules, components or elementary flows that contribute most to the overall life cycle GWP impacts, support design improvements and strategic improvement plans. According to Product Environmental Footprint (PEF) category rules guidance, hotspots contribute to at least 80% of any of the most relevant impact categories identified (i.e., GWP). Moreover, if the use stage accounts for more than 50% of the total impacts, it is expected the possibility to the re-run the hotspot analysis graph by excluding the use stage. In this case, the list of most relevant life cycle stages shall be those selected through the latter procedure plus the use stage. All these in-depth outcomes are included into the platform section dedicated to LCA.

5.4. Circularity related output

Although the circularity checklist is not yet in its final form, it is envisaged that the output will be represented as a percentage from 0 to 100, which indicates the building's level of maturity in terms of meeting circular economy principles.

5.5. Multi objective optimization

Implementing the circular economy paradigm within the built environment presents a range of challenges, particularly when balancing the need for substantial investments and the pursuit of ambitious decarbonization targets. These challenges are amplified when considering both embodied and operational energy consumption and carbon emissions. Embodied energy refers to the total energy used in the production of materials, technologies and the construction process of a building, while operational energy pertains to the energy consumed during the building's use. Reducing carbon emissions across both of these domains is essential but requires significant financial investment for technological upgrade, which very often acts as a constraint in the optimization process of building retrofits.

In the context of building refurbishment, investment costs and carbon emissions serve as critical constraints in the multi-objective optimization process. The investment cost is largely dictated by the available budget for building refurbishment, making it a key limiting factor, constraining the possible design choices. On the other hand, reducing carbon emissions is a fundamental objective (one of the main reasons) of refurbishment efforts, as it aligns with broader goals of sustainability and climate change mitigation at global scale.

Although many indicators are calculated as part of the Life Cycle Assessment (LCA) procedure—such as energy use, resource depletion, and environmental impact—optimizing refurbishment decisions becomes increasingly complex when many indicators (such as the ones pertaining to a LCA and circular economy) are involved. Even if various multi-criteria evaluation approaches are available at the state-of-the-art, it can be challenging for non-experts to apply them effectively in normal design practice. The intricacies involved in understanding and implementing these methods often act as a barrier to their widespread adoption in practical settings.

To address this complexity and make the optimization process more accessible, the chosen approach focuses first on representing the trade-offs between global cost (which includes both initial investment and operational costs), primary energy use, and carbon emissions, considering both embodied and operational energy in the computational process. After that, LCA and circular economy indicators are computed and presented to the user.

This approach is consistent with previous research conducted during the HEART project and extends the well-established cost-optimal analysis methodology [39]. Over the years, this methodology has been consolidated and discussed extensively in the literature [40]. Cost-optimal analysis traditionally involves a two-objective optimization (global cost versus primary energy or carbon emissions [41]) where the optimal solutions lie on the Pareto frontier [42], a concept that allows these solutions to be identified both graphically and numerically, by selecting "non-dominated" solutions. This two-objective optimization has proven to be highly insightful, as demonstrated in numerous studies at European level [43].

The solutions located on the Pareto frontier serve as a starting point for identifying a collection of optimal alternatives that fulfil both investment and decarbonisation objectives, hence limiting the pool of available solutions that achieve a favourable balance between financial viability and environmental impacts.

Once the Pareto optimal solutions are identified (from the original set of solutions), a comprehensive set of LCA and circular economy indicators is then computed for each cost-optimal solution and can be plotted with dedicated visualization strategies to highlight key insights and support the decision process. By means of this additional layer of analysis, users can assess the best performing options based on environmental (LCA indicators) and circular economy impact considerations, while still complying with their specific budget constraints and decarbonisation objectives.

This simplified yet comprehensive approach is meant to enable stakeholders to engage with the optimization process without requiring necessarily deep expertise in multi-criteria evaluation methods. By combining these insights, the multi-objective optimization framework offers a robust tool for guiding sustainable and cost-effective building retrofits in line with environmental and circular economy principles.

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6. ANNEX - RE-SKIN Decision Support System: Functional Description

6.1. Databases

There are 5 Databases needed to implement the model:

1. **technologiesDB**: All the technologies and their characteristics (included embodied carbon and primary energy inclusion) *(see Compositions in Appendix)*
2. **localsDB**: Data locals to a site, for example monthly mean temperature and relative humidity levels.
3. **Solar_geometry**: Solar exposition by location following solar exposure.
4. **pvplantpvgis**: Data from Photovoltaic Geographical Information System to evaluate potential of photovoltaic systems following location.
5. **lcaDB**: Secondary database with general data.

6.2. Parameters

There are 3 sets of parameters needed for the model to run:

1. **Buildinginput**: All the parameters specifics to the building site *(see Compositions in Appendix)*
2. **modelparams**: Parameters pertaining specifically to the model *(see Compositions in Appendix)*
3. **Factors**: Parameters concerning the specific schedules of ventilations, cooling and heating. Gains, attenuation and grid interactions related factors.

6.3. Main Structures

1. **technologies**: A "Technology" is a type of technology to be installed in the building. There are currently 11 technologies:
    a. Windows (new windows, new insulation, etc.)

b. Basement (insulation)

c. Roof (insulation)

d. Wall (insulation)

e. Heat Pump

f. Thermal Storage

g. Multiple Input Multiple Output (MIMO)

h. Smart Fan Coil Heating, ventilation and air conditioning (HVAC)

i. Smart Fan Coil Hot Domestic Water (HDW)

j. Batteries

k. Photovoltaic installation

There are several possible types of each technology to choose from. For example, thickness of insulation of the walls, power and capacity of heat pumps, type of batteries, etc.

Each technology has two types of member data (*field*): those that are common to all the technologies (for example unit price, life time) and one set of specifics that will be used technology by technology for computation.

2. **Installation**: One occurrence of "Installation" is an array of a choice within the 11 technologies, possibly with a zero value if the technology is not implemented. For each technology, the model computes the optimal amount of materials needed following the building parameters.

   The gain of efficiency is computed technology by technology and month by month. An economic and CO_2 eq computation is then applied to the results.

   Because of the high number of possible installations, the non-linear characteristics of the gains, the high number of parameters involved, and the non-uniqueness of the decision criteria, it is not possible to find a unique optimum installation.

   The decision support system (DSS) computes a set of possible installations and publishes the set of results, from which a set of 3 or 4 optimum installations should be chosen. Let us notice that, arithmetically, if we had simply 3 possible choices to select from for each technology, the theoretical number of possible installations would be 3^{10}, that is 59,049 possible installations!

7. ANNEX - Building Circularity KPIs table – extended version

Building Circularity Indicators (FoBCIs) for Products – SHORT LIST														
							Phases				Boundary			
#	Indicator	Description	Source	Unit of Measure	Content	Attitude	ex-ante	manufacturing	construction	ex-post	Building	RE-SKIN System	Component	Notes
S.1	Resource inflows: renewable products and materials	The undertaking shall include in tonnes or kilo: the weight in both absolute value and percentage of **renewable** input **materials** from **regenerative sources used to manufacture** the undertaking's products and services (including **packaging**); N.B. The undertaking shall provide information on the methodologies used to calculate the data. It shall specify whether the data is sourced from direct measurement or	European Sustainability Reporting Standards Exposure Drafts (ESRS) by European Financial Reporting Advisory Group (EFRAG)	Kg, Tons and %	X		X	X		X	X	X	X	For the calculation at component level (i.e., façade, BIPV roof, …) the indicator shall be first calculated for the single elements (e.g., for the façade the aluminium mullions, the insulating panels, etc)

		estimations, and disclose the key assumptions used.												
S.2	Resource inflows: reused products and materials	the undertaking shall include in tonnes or kilo: the weight in both absolute value and percentage, of **reused or recycled products and materials** (= non-virgin) used to manufacture the undertaking's products and services (including packaging). N.B. The undertaking shall provide information on the methodologies used to calculate the data. It shall specify whether the data is sourced from direct measurement or estimations, and disclose the key assumptions used.	European Sustainability Reporting Standards Exposure Drafts (ESRS) by European Financial Reporting Advisory Group (EFRAG)	Kg, Tons and %	**X**			**X**		**X**		**X**	**X**	For the calculation at component level (i.e., façade, BIPV roof, …) the indicator shall be first calculated for the single elements (e.g., for the façade the aluminium mullions, the insulating panels, etc)

S.3	Resource inflows: recycled products and materials	the undertaking shall include in tonnes or kilo: the weight in both absolute value and percentage, of **reused or recycled products and materials** (= non-virgin) used to manufacture the undertaking's products and services (including packaging). N.B. The undertaking shall provide information on the methodologies used to calculate the data. It shall specify whether the data is sourced from direct measurement or estimations, and disclose the key assumptions used.	European Sustainability Reporting Standards Exposure Drafts (ESRS) by European Financial Reporting Advisory Group (EFRAG)	Kg, Tons and %	**X**			**X**		**X**		**X**	**X**	For the calculation at component level (i.e., façade, BIPV roof, …) the indicator shall be first calculated for the single elements (e.g., for the façade the aluminium mullions, the insulating panels, etc)
S.4	Resource inflows: remanufactured/repurposed/reconditioned products and materials	the undertaking shall include in tonnes or kilo: the weight in both absolute value and percentage, of **remanufactured/repurposed/reconditioned products and materials** (= non-virgin) used to manufacture the undertaking's products and services (including packaging). N.B. The	European Sustainability Reporting Standards Exposure Drafts (ESRS) by European Financial Reporting Advisory Group (EFRAG)	Kg, Tons and %	**X**			**X**		**X**		**X**	**X**	For the calculation at component level (i.e., façade, BIPV roof, …) the indicator shall be first calculated for the single elements (e.g., for the façade the aluminium mullions, the insulating panels, etc)

		undertaking shall provide information on the methodologies used to calculate the data. It shall specify whether the data is sourced from direct measurement or estimations, and disclose the key assumptions used.												
S.5	Virgin raw materials	% of virgin raw materials	European Sustainability Reporting Standards Exposure Drafts (ESRS) by European Financial Reporting Advisory Group (EFRAG); BS ISO 20887:2020 - Sustainability in buildings and civil engineering works. Design for disassembly and adaptability; Ellen MacArthur Foundation (EMF)	%	**X**			**X**		**X**		**X**	**X**	

S.6	Recyclable content	% of recyclable content	European Sustainability Reporting Standards Exposure Drafts (ESRS) by European Financial Reporting Advisory Group (EFRAG); BS ISO 20887:2020 - Sustainability in buildings and civil engineering works. Design for disassembly and adaptability	%	**X**		**X**	**X**		**X**	**X**	**X**	**X**	
S.7	Reusable content	% of reusable content	European Sustainability Reporting Standards Exposure Drafts (ESRS) by European Financial Reporting Advisory Group (EFRAG); BS ISO 20887:2020 - Sustainability in buildings and civil engineering works. Design for disassembly	%	**X**		**X**	**X**		**X**	**X**	**X**	**X**	

			and adaptability											
S.8	Waste at disposal	% of waste generated for the manufacturing and installation of RE-SKIN system that is sent at disposal	European Sustainability Reporting Standards Exposure Drafts (ESRS) by European Financial Reporting Advisory Group (EFRAG); BS ISO 20887:2020 - Sustainability in buildings and civil engineering works. Design for disassembly and adaptability; Ellen MacArthur Foundation (EMF)	%	**X**			**X**	**X**			**X**	**X**	the calculation shall be done considering the waste generated by the installation of the RE-SKIN system on a building

S.9	Resource outflows: waste to recovery	The manufacturer shall disclose in tonnes or kilogrammes: for each type of hazardous and non-hazardous **waste**, the percentage of waste diverted from disposal by **recovery** operation type and the total amount summing all three types. The **recovery** operation types to be reported on are: i. preparation for **reuse**; ii. **recycling**; and iii. other recovery operations;	European Sustainability Reporting Standards Exposure Drafts (ESRS) by European Financial Reporting Advisory Group (EFRAG)	Kg, Tons	**X**			**X**		**X**		**X**	**X**	possibly separate hazardous and non-hazardous
S.10	Outline Waste Management Plan (WMP)	**Presence of WMP** to explain (i) how environmental and health impacts from CDW can be **reduced**; (ii) how cost benefits can be maximised (i.e. increased revenues and avoided costs) and (iii) how the segregated collection of **onsite waste** can be optimised based on the different possible end market, storage, processing and disposal options.	Level(s) 2.2 - Level 1		**X**				**X**			**X**	**X**	

S.11	Elements and their parts are independent and easily separable	The potential to separate **building elements** that are connected to each other and to **disassemble** elements into their constituent components and parts.	Level(s) 2.4 - Level 1			X		X	X			X	X	Ease of disassembly
S.12	Connections are mechanical and reversible	The use of mechanical, non-destructive **connections** as opposed to chemical bonding.	Level(s) 2.4 - Level 1			X		X	X			X	X	Ease of disassembly
S.13	Connections are easily accessible and sequentially reversible	Easy and sequential access in order to reverse mechanical **connections** and remove elements, components or parts.	Level(s) 2.4 - Level 1			X		X	X			X	X	Ease of disassembly
S.14	Specification of elements and parts using standardised dimensions.	Specification of **elements and parts** that are of a **standardised** specification in order to provide consistent future stock.	Level(s) 2.4 - Level 1			X		X	X			X	X	Ease of reuse
S.15	Specification of modular building services.	Specification of **modular** systems that may retain value upon de-installation or which may be more easily swapped out and upgraded.	Level(s) 2.4 - Level 1			X		X	X			X		Ease of reuse

S.16	Parts made of homogenous materials with minimal unnecessary treatments or finishes	Specification of **components and constituent parts** made of homogenous materials, the same materials or materials mutually compatible with **recycling** processes. N.B. Finishes, coatings, adhesives or additives should not inhibit recycling.	Level(s) 2.4 - Level 1			X		X				X	X	Ease of recycling
S.17	There are established recycling options for constituent parts or materials	The **part or material** is readily **recyclable** into products with a similar field of application and function, thereby maximising their circular value.	Level(s) 2.4 - Level 1			X		X	X			X	X	Ease of recycling
S.18	Reusability	— practically reusable or not — for a product to be deemed **reusable**, there needs to be an application that allows an end-user to economically re-use the product without extensive cleaning or restoration; Re-use can be graded on a continuum, ranging from re-use of the entire structure to re-use of selected materials;	BS ISO 20887:2020 - Sustainability in buildings and civil engineering works. Design for disassembly and adaptability			X		X	X			X	X	

S.19	Comparison of lifetimes and sequence of possible renovation measures	Have the **service life** of the building **materials** applied been coordinated so that no intact building materials or components have to be damaged in future **renovation** measures?	Deutsche Gesellschaft für Nachhaltiges Bauer (DGNB) - German Sustainable Building Council			**X**		**X**			**X**	**X**	**X**	

Figure 13. Building Circularity KPIs table – extended version