Climate and cultural based design and market valuable technology solutions for Plus Energy Buildings

Guidelines and calculation methods for Lifecycle Environmental Impact Assessment of Plus Energy Buildings

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List of abbreviations

PEB	Plus Energy Building
nZEB	Net Zero Energy Building
GWP	Global Warming Potential
PERT	Primary Energy Renewable Total
PENRT	Primary Energy Non-Renewable Total
RES	Renewable Energy Systems
TES	Thermal Energy Storage
PCR	Phase Change Materials
PV	Photovoltaics
EoL	End of Life
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
BoQ	Bill of Quantities
LCIA	Life Cycle Impact Assessment
DHW	Domestic Hot Water
DU	Declared Unit
FU	Functional Unit
BoM	Bill of Materials
DCS	Data Collection Sheet
PCR	Product Category Rules
BBSR	Federal Institute for Research on Building, Urban Affairs and Spatial Development German: Bundesinstitut für Bau-, Stadt-, und Raumforschung

1 Executive Summary

This document aims to collect and report the results of the activities ongoing within the EU-funded Cultural-E project (under grant agreement No. 870072).

As a prior result of the Cultural-E activities, a document has been prepared, in which the guidelines and calculation methods for carrying out environmental impact assessment on Plus Energy Buildings (PEBs) are outlined. The document is targeted to building developers and provides the audience with an operative methodology for dealing with Life Cycle Assessment (LCA), in compliance with standards ISO 14040 [1]. ISO 14044 [2]. For the compilation of the guidelines, core rules for the lifecycle modelling and impact calculation methods have been considered also specifications for buildings and building products, provided by EN 15804 [3], EN 15643 [4] and EN 15978 [5].

Task 4.5 of project Cultural-E demonstrated in fact the need for an adaptation and clear specification of LCA analyses for PEBs' systems. This is mostly due to complexity of workflows and data to be handled as well as the novelty of the investigated systems. This document presents therefore to building developers a framework and, consequently, a procedure for LCA analyses of systems designed and developed for Plus Energy Buildings (PEBs).

Such a procedure allows for a clear establishment of the LCA goal and scope. The PEBs systems are while evaluate through a bottom up approach, which, depending on the goal and scope of the analysis, extracts relevant information from specific outcome and finally proceed with the Life Cycle Inventory (LCI) and environmental impacts assessment. For a correct results' derivation, it is important to choose and agree on adequate lifecycle modelling tools and match the collected information with suitable environmental datasets

In addition to this, the report contains further outcomes coming from the above-mentioned activities.

The assessment of PEBs' technologies (in this instance, Active Window System – AWS, NORDIC® ECO smart air movement, Packed Heat Pump – PHP and the High-capacity Hybrid Storage system – HCHS) is targeted to products developers. It serves as a reference for the evaluation of the environmental potential of such components and the identification of optimization potential.

The parametric LCA modelling of PEBs' climate and cultural tailored solution sets is while addressed to building developers. It highlights advantages and challenges to be handled while designing PEBs in specific climate and cultural contexts. In this respect, it can be used within the project also as a reference for the next upcoming steps and especially for the lifecycle analyses of the designed demo cases.

2 Introduction and Context

2.1 Document Structure

Here below is presented the structure of the document and the audience targeted (Figure 1).

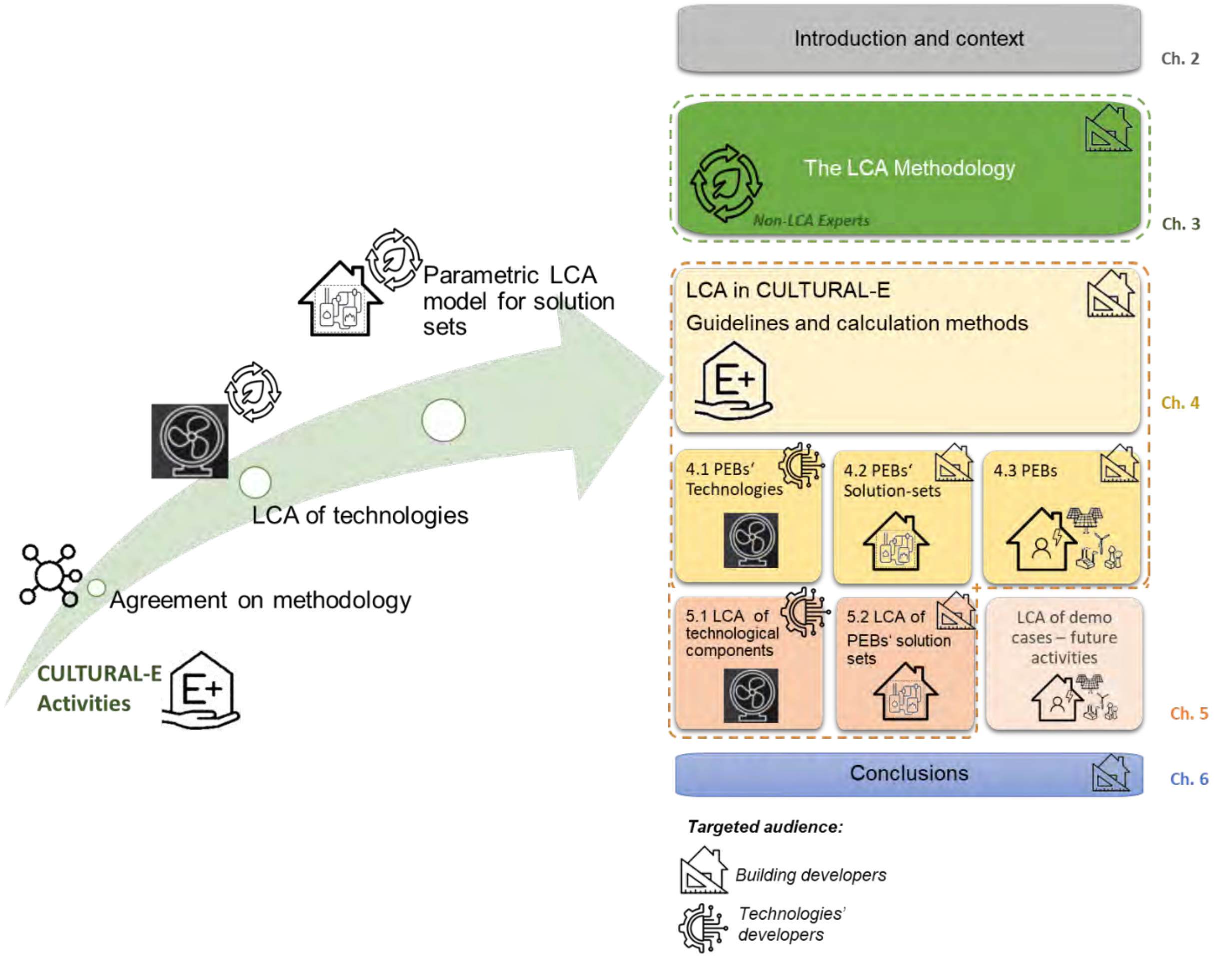

Figure 1: Document structure and targeted Audience.

This document collect the results coming from Cultural-E activities aimed to provide environmental impact assessment of PEBs' climate and cultural tailored solution sets.

As a preliminary step of the carried out activities, decisions regarding the methodology have been taken. Based on such an agreement, as a first step, LCA analyses of developed technologies occurred: in doing this, information was gathered for understanding environmental potential and optimization possibilities. This activity led to discussion and recommendation to technologies' providers for guiding their engineering process. As a second step, parametric LCA models for evaluating the solution sets in buildings have been produced, keeping in consideration KPI framework, energy related habits, tech solutions, and looking forward to the analysis on foreseen for demo cases (next to come in the project).

Finally, as a prior result of the conducted activities, guidelines on how to understand and re-do the above steps in a specific case are provided.

Despite the confidentiality of some models, results are provided to the reader. The assessment of PEBs' technologies (in this instance, Active Window System – AWS, NORDIC® ECO smart air movement, Packed Heat Pump – PHP and the High-capacity Hybrid Storage system – HCHS) is targeted to products developers. It serves as a reference for the evaluation of the environmental potential of such components and the identification of optimization potential.

The parametric LCA modelling of PEBs' climate and cultural tailored solution sets is while addressed to building developers. It shows advantages and challenges to be handled while designing PEBs in specific climate and cultural contexts. In this respect, it can be used within the project also as a reference for the next upcoming steps and especially for the lifecycle analyses of the designed demo cases.

Lastly, this document includes a part dedicated to the Life Cycle Assessment (LCA). Here, when required, the reader has access to fundamentals and main definitions of the currently applied methodology, according to international standards.

2.2 Relevance of Environmental Assessment in Cultural-E

Despite the efforts and the record levels of renewable energy sources in the European contexts, the construction industry still presents a slower shift away from the direct use of coal, oil and traditional biomass towards renewable sources. According to the 2021 Global Status Report for Building and Construction, the pandemic-induced changes [1] and now war-related risks, which had consequences also on the energy demand during the building operation and related CO2 emissions. This change reflects a shift from the commercial and retail sectors to the residential sector. For these reasons some initiatives have been already undertaken (REPowerEU plan [2]) and the next five years are critical and require a wide adoption of transformational approaches and a full stakeholders' engagement to create a zero-carbon built environment. [3].

In this context, energy efficient buildings (passive, zero energy) offer new perspectives for a concrete reduction of energy consumption and consequent emissions during building operation. Plus Energy Buildings (PEBs) has received increasing attention in recent years. Their potential has been discussed in studies, while not yet demonstrated [4–7]. Due to their novelty also, their environmental relevance of this concept is often questioned [8]. In fact, PEBs may present higher amount of materials and or require more installation components, which in a lifecycle perspective must be accounted in order to evaluate the environmental potential of the building over the whole lifecycle [8]. Cultural-E aims to present modular and replicable solutions for Plus Energy Buildings (PEBs) that match selection and interaction of technologies to cultural and climate aspects, by fostering energy savings. The latter is allowed with the application of RES, photovoltaic panels - and thermal solar collector to be coupled with storage systems. A PEB aims to reduce not only its energy consumption during the building operation, but also the life cycle impacts over the building lifecycle.
Solutions sets are group of building elements and technological systems, and are the main objective of LCA analyses carried out during the activities. However, they can include one or more from project technologies that can operate as a whole to meet PEB requirements. Due to their novelty, environmental information may lack. Hence, the assessment of solution sets is anticipated by an investigation on novel products and technologies, for which environmental analyses are missing. These are in this instance:

- *Active Window system (AWS)* developed by Eurofinestra
- *Smart air movement for thermal comfort* developed by Vortice
- *Packed heat pump system (PHP):* delivered by Ventive
- *Compact high-capacity hybrid storage (HCHS)* from Brunel University

The House Management System (HMS) has been not included, since it is mainly on the working on cloud. The environmental impact avoided due to energy savings and its installation in PEBs' systems are therefore deemed more relevant.
With respect to the project technologies, due to their innovation content and the stage of development, feedbacks on environmental impact can effectively drive engineering and marketing choices towards more sustainable alternatives. A comparison against traditional components can boost a discussion with technology developers, bringing the theme of environmental impact in discussions usually limited to technical requirements and cost performances.
Starting from the knowledge acquired regarding technological components, a variety of possible combinations for climate and cultural tailored solutions set is possible. However, the definition and the choice of suitable solution-sets (best option) in a

specific building and context should be carried out in a holistic way, i.e., by trading-off environmental impacts as well as technical, social, economic aspects and climate-cultural context.

During the activities, three system levels are identified (PEBs' technologies, solution sets and the whole building). Each of them needs to be developed and finally assessed in their environmental performance, among KPIs in the PEB evaluation framework. Having environmental assessment at hand allows for benchmarking design alternatives against environmental impacts. In addition to this, in analogy with the economics, PEBs may require a higher "environmental investment", due to higher amount of materials and components (e.g., Photovoltaic systems), but also generate environmental credits, related to avoided carbon emissions.
All the above-mentioned investigations can be carried out with help of Life Cycle Analyses and, more precisely, Life Cycle Assessment (LCA), which can provide useful tools and support stakeholders during the decision-making process and are therefore chosen as basis for the environmental impact assessment of solution sets.

Nevertheless, the novelty and the complexity of the data to be handled required still a preliminary agreements and decisions in order to identify a proper operative methodology and eventual adaptations specific for LCA analysis of PEBs.

Overall, the experience collected in the Cultural-E activities served as a lesson-learned. This document therefore reports this experience in form of a "guideline" on "how to" re-do same steps in their conditions and such. The guideline can be a useful instrument for getting indications regarding the clear establishment of LCA goal and scope, based on current standards. Afterwards, it provides calculation methods, by including the used data tools for Life Cycle Inventory and Impact Assessment. In order to understand complexities and trade-offs inherent in the LCA study, all necessary steps need to be transparent and documented, by including also methods, assumptions and limitations[9].

Finally, for the sake of completeness, some of the carried out LCA analyses have been collected, and their results here presented and discussed.

3 The Lifecycle Assessment Methodology

3.1 Description of the life cycle assessment methodology

According to the definition in ISO 14040, Life Cycle Assessment (LCA) is the "compilation of an inventory of relevant energy and material inputs and environmental releases" [9]. Through LCA it is possible to evaluate potential environmental impacts associated with identified inputs and releases over all the stages of a product's life.

In the field of LCA, the term life cycle must be understood as the flow-oriented cyclical life cycle concept (see Figure 2). First, the primary product must be obtained. This raw material is used to produce intermediate products of all kinds, which in turn combine with other intermediate products to produce a final product. This is followed by the use phase. In the recycling process, the product is returned to the life cycle phases in different ways. The recycled products are broken down into their individual components and made available for pre-production. This can result in major savings, as the primary product no longer needs to be dismantled, thus conserving resources. However, if the product is no longer usable and cannot be returned to its life cycle, it has to be disposed of, and the product has to be recycled.

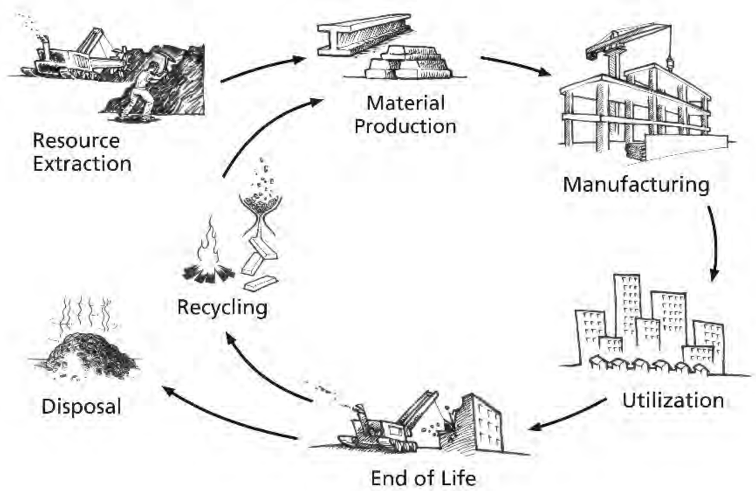

Figure 2: Description of product "lifecycle".

The basic idea of LCA is to solve problems that have already arisen or are arising and not to "shift" them from one life cycle phase to the next ("*shift of burdens*" concept). In addition to this, the aim is to avoid creating new problems even if others could be solved. In this problem-solving process, it is important to consider different impacts in order to achieve an optimal environmental profile.

Principles and framework of Environmental lifecycle assessment (LCA) are defined in standards ISO 14040 [9], while the requirements and guidelines are defined in ISO 14044 [10]. LCA analyses have several applications: through the provision of environmental feedbacks, designers can be informed on the ecological situation in the entire life cycle, compare products and services, develop and improve them. Furthermore, LCA studies can be used for strategic planning, marketing and on higher levels, for public policy making [9].

The process of environmental impact assessment in an LCA study (Figure 3) is carried out in four steps. In the first phase of the LCA study, the goal of the analysis is defined. Depending on this, the system boundary, the level of detail of analysis and a functional unit are defined.

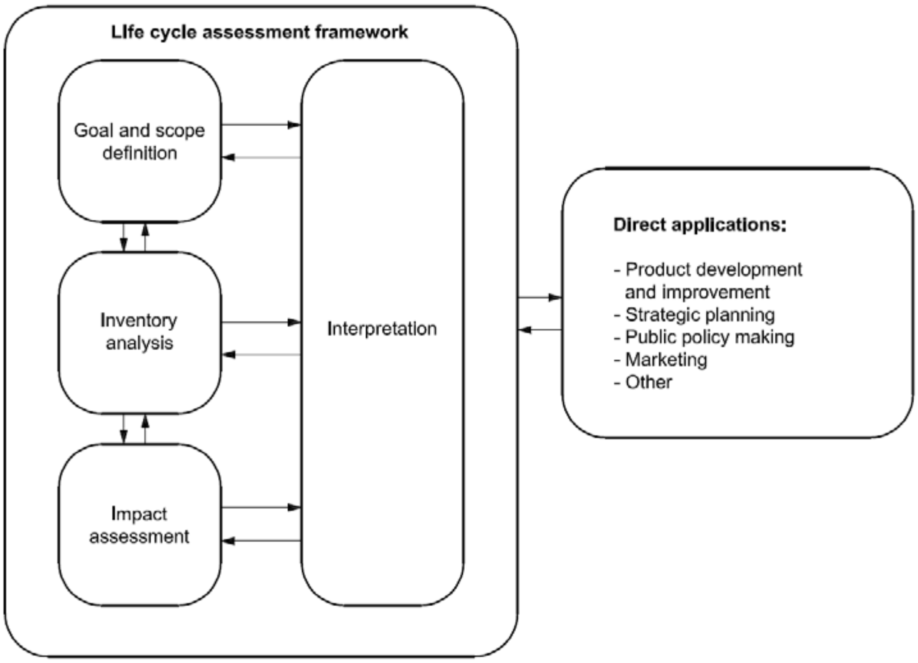

Figure 3 Stages of an LCA [9].

Within the Life Cycle Inventory (LCI) phase, consistently with the previous assumptions, all relevant data on the materials and technologies needs to be collected. This leads to the definition of input and output flows of the system. Analysis involves creating an inventory of flows from and to nature for a product system, where inputs are water, energy, and raw materials, and outputs are the releases to air, land, and water. All information is provided referring to a reference unit.

In the Life Cycle Impact Assessment (LCIA) phase, the purpose is to provide a well-defined assessment of considered environmental impact categories, based on the product system's LCI results. In this phase, for each impact category, a characterization process is carried out. Optional LCIA elements are normalization, grouping, and weighting, which may be conducted depending on the goal and scope of the LCA study.

Lastly, all results coming from the previous phases are interpreted, i.e., summarized, discussed and followed by decision-making strategies in accordance to the goal and scope definition [9,10]. Within results discussion, issues regarding assumptions and results accuracy, completeness and precision may arise. These can be solved by improving the performed LCI and consequently enhancing the LCIA. As shown in Figure 3, LCA is therefore an iterative process, where all stages are interdepended.

In field of construction, supplementary standards have been established. In EN 15804 [11], core rules for the product category of construction products and Environmental Products Declaration (EPD) are presented. This are the basis in this work for the evaluation of the analyzed PEBs' technologies. In EN 15643 the sustainability assessment of buildings and civil engineering work is established [12], while EN 15978 presents the calculation method [13]. Both, are used as basis for the assessment of solution sets and PEBs. Annex A1 of EN 15804 [11] is considered for environmental impacts' characterization.

3.2 Goal and scope of the assessment

An LCA starts with the goal and scope of the study, which is an explicit statement of context and an explanation targeted audience and results communication. As stated in ISO standards, it is a key step, in which the object of the analysis is defined together with analysis's aim (goal). Within the scope, the following points are while clearly defined in order to ensure consistency with the intended application:

- System boundaries definition
- Functional unit establishment
- Key assumption for the analysis (cut-off criteria)
- Selection of impact categories to be analysed

3.3 System boundaries

The system boundaries determine which unit processes are to be included in the LCA study. Defining system boundaries is partly based on the scope phase and consequently on subjective choices but they can be based on the analyzed technological system and nature [14].

In this regard, the geographical area and different ecosystem sensitivity can have a crucial role.

For instance, services such as energy production, waste management and transport systems, can differ from one region to another. Boundaries must consider time horizon as well, since LCAs are carried out to evaluate present impacts and predict future scenarios. Time horizon boundaries should be limited consistently with technologies involved and pollutants lifespan. On technological systems, interrelations among product systems can be considered as well.

3.4 Functional unit, Functional equivalent and declared units

ISO 14040 and 14044 define the 'functional unit' as the quantification of the performance of a product system, and specify that it is used as the reference unit for the LCA and any comparative assertion [9,10]. Together with the ISO definitions, there are others provided in CEN standards, which are specific for the building sector.
EN 15804 defines a functional unit and a declared unit [11], while EN 15978 defines a functional equivalent [13].
For buildings and construction works, the term 'functional unit' refers to the *quantification of identified functions or performance characteristics of products* [11]. The functional unit is used primarily as the reference unit for the products LCA study and comparisons [15]. It is the unit of scale or reference on which the LCA results are based, and relates to the given function of the product. In many cases, the functional unit should be defined according to the future use of the building.
A functional unit usually comprises:

- the product functions
- a quantity
- a duration for LCA analysis
- a quality characteristic [15,16].

In the instance of a building with dwelling function, [m^2 (net surface dwelling) * y] is commonly used as functional unit. It contains the specification of the function and a quality characteristic (building dwelling), a quantity (m^2), a duration (y). Provided two buildings with identical function, the total impacts can be provided in terms of functional unit in order to allow comparisons. Further details and considerations on functional units are reported in sections 4.1.3, 4.2.3 and 4.3.3.
In building LCA, the term 'functional equivalent' denotes the technical characteristics and functionalities of the building that is being assessed, i.e., building type, relevant technical and functional requirements, the pattern of use and the required service life [13]. Differently from the functional unit, it does not include a quantity. In this sense, the functional equivalent intends to describe the overall building characteristics and performances.
Finally, the term 'declared unit' is specific to product LCAs, as stated in EN 15804. It is used instead of the 'functional unit', if the specific function of a product at the building level is not known [11]. EN 15804 states that the declared unit shall be used if an LCA study does not cover the entire life cycle ('cradle to grave'), but only certain modules (e.g., only 'cradle to gate', product manufacturing only). The terms should be used in line with the definitions of the standards to allow for improved consistency of LCA studies within the construction sector [15,16]. More details regarding products reference unit are provided in section 4.1.3 in chapter 4 for each of the analyzed technology.

3.5 System boundaries in buildings and cut-off criteria

The system boundaries in an LCA analysis define which parts of the life cycle and which processes belonging to the analyzed system are required to provide the final system function, as defined by its functional unit [9,14]. The definition of the system boundaries is important to ensure that all processes are included in the modelled system and that any relevant potential impacts on the environment are appropriately covered.
For buildings, system boundaries are established in regards to life cycle phases (see Figure 4) [13].

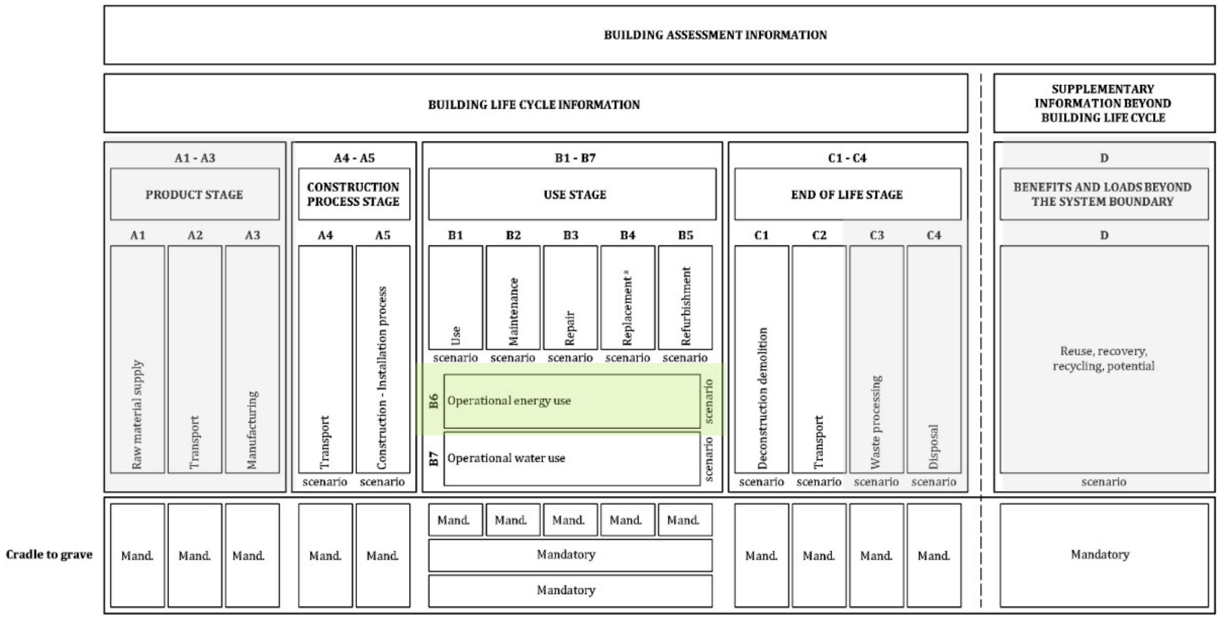

Figure 4 - Life cycle stages in a cradle-to-grave system boundary [13].

With the collection of the building information, several lifecycle phases can be distinguished. In buildings, the information proceeds from product manufacturing (A1-A3), through construction work processes (A4-A5), actual use including maintenance, refurbishment and operation of the building (B1-B7), and finally at the end of life, de-construction or demolition, waste processing in preparation for reuse, recycling and energy recovery (C1-C4; D). In Figure 4 the relevant information available in most building LCA studies is marked. In fact, for most of the study the integration of the components in the building (A5: Construction phase) and the process of extraction of the components from the building (C1: De-construction phase) are excluded due to lack of data availability. Grey marked and in the Figure 4 vertical positioned are the phases included for the calculation of Embodied Impact (EI). Horizontal positioned are while the phases accounted for Operative Impact (OI).

3.6 Environmental impact assessment: categories and indicators

The main goal of environmental indicators is to communicate information about the environment and how human activities affect it, to highlight emerging problems and draw attention to the effectiveness of current policies. Indicators should tell us, briefly, whether things are getting better or worse. Indicators should reflect changes over a period of time tailored to the problem, be reliable and reproducible, and, whenever possible, be calibrated in the same terms as the policy goals or linked targets [17].

LCIA is about the quantification of potential environmental impacts caused by the supply chain of products and services (product LCA), as well as by the activities of organizations including the upstream and downstream suppliers [9,18]). LCIA methods, environmental impact category indicators, and environmental damage indicators are thus challenged by numerous and complex supply chains that span the globe and spread over several years, if not decades.

Core lists of environmental issues and of relevant indicators have been and are being developed by several organizations, building on the OECD's initial work [19].

The information on environmental impacts is expressed with the impact category indicators of Life Cycle Impact Assessment (LCIA) using characterization factors in a LCIA according to ISO 14044. Information on the impact categories, indicators, characterization methods, units and characterization factors to be applied is stated in Annex C. In the building sector, EN 15804 contains a core set of pre-determined environmental indicators (see Table 1) [11]. Environmental indicators help to assess the environmental impact of process releases. In order to achieve better transparency of the description of the environmental quality of construction products by the environmental impact indicators, two groups of indicators and environmental information must be declared based on the life cycle inventory.

Table 1: Core indicators list for building products, according to [11].

Global warming Potential — total, fossil, biogenic, land use and land use change	GWP-total, fossil, biogenic, land use and land use change	kg CO2-eq.
Ozone Depletion	ODP	kg CFC-11-eq.
Acidification Potential	AP,	mol H+-eq.
Eutrophication fresh water	EP-Fresh Water	kg PO4-eq.
Eutrophication sea water	EP-Sea Water	kg N-eq.
Eutrophication Land	EP-Land	mol N-eq.
Photochemical Ozone Creation Potential	POCP	kg NMVOC-eq.
Abiotic Depletion Potential — Minerals and Metals	ADP	kg Sb-eq.
Water consumption	WDP	m^3 World eq.

Renewable primary energy as energy carrier	PERE	MJ

Renewable primary energy resources as material utilization	PERM	MJ
Total use of renewable primary energy resources	PERT	MJ
Non-renewable primary energy as energy carrier	PENRE	MJ
Non-renewable primary energy resources used as raw materials	PENRM	MJ
Total use of non-renewable primary energy resource	PENRT	MJ
Use of secondary material	SM	kg
Use of renewable secondary fuels	RSF	MJ
Use of non-renewable secondary fuels	NRSF	MJ
Use of net fresh water (FW)	FW	m^3

Global Warming Potential

Standard LCIA methods incorporate the developments on the science around emission metrics and climate impacts. CO2 and other GHGs, aerosols, and ozone precursors affect the radiation absorption properties of the atmosphere. The resulting change in temperature affects both natural ecosystems and human societies in multiple ways.
The state of art refers mainly to the summarized outcomes of IPCC and assess climate change impacts in LCA in a single indicator, i.e. kg CO2 eq. This value includes the weighted sum of WMGHGs (e.g., CO2, CH4, N2O, SF6, CFCs, and other halocarbons), which have a lifetime of years to millennia, and NTCFs, which have lifetimes in the atmosphere of days to weeks (see ANNEX I - Description of impact categories). The so-called GWP 100-year environmental proxy for the potential temperature rise from short-lived WMGHGs in about four decades. Regarding spatial and temporal characterization, climate impacts from WMGHGs are insensitive to emission regions, while NTCFs, whose climate impacts are dependent on the emission location [20,21].

Acidification Potential

The AP summarizes all substances that lead to acidification in relation to the effectiveness of SO2. The conversion of air pollutants to acids causes the PH-value of the precipitation to decrease (acidify). The result is acid rain with acidification of soil and water. Secondary consequences on buildings are corrosion of steel, decomposition of natural stone, concrete and clay [22].

Eutrophication Potential

The EP summarizes substances in comparison to the PO43-effect together. Over-fertilization can lead to the accumulation of human-toxic substances in ground, drinking water and soils. Examples of the effects of over-fertilization are fish mortality, weakened plant growth or, in case of formation to nitrite, serious toxic consequences for human health [23].

Abiotic depletion potential for fossil and non-fossil resources

The main concern of this category is the health of humans and the ecosystem and how it is affected by the extraction of minerals and fossil fuels, which are inputs into the system. For each extraction of minerals and fossil fuels, the abiotic depletion factor is determined. This indicator is on a global scale [24].

Primary energy consumption

Primary energy consumption measures the total energy demand of a country (see ANNEX I - Description of impact categories). It includes:

- consumption of the energy sector
- losses during transformation
- distribution of energy,
- the final consumption by end users.

Energy carriers used for non-energy purposes (such as petroleum not used not for combustion but for producing plastics) are not included.

The total primary energy consumption is determined by the Working Group on Energy Balances (AGEB) on the basis of efficiency ratios [25]. In LCA studies, the total primary energy consumption can also be analyzed with consideration to the share of renewable (Primary energy renewable total – PERT) and nonrenewable energy (Primary energy nonrenewable total – PENRT).

Looking at the current trend and policies, reduction of energy consumption is required in households, starting from heating and cooling, mobility, appliances, by recalling sobriety choices.

However, energy consumption can be obtained also by increasing energy savings and by allowing a switch to renewable and not pollutant energy sources.

3.7 Environmental information and databases

Over the past 20 years, different generic LCA databases have been developed, such as ecoinvent [26], GaBi [27], DEAM, and US-LCI [28].
In that context, two main categories of LCA databases are found in practice: (1) the generic databases mainly provided by academics and consultancy firms, e.g., ecoinvent centre, PE International, and EC-JRC consisting partly or mainly of generic data; and (2) databases provided by industry that are sector- or product-specific, e.g., Environmental Product Declaration for building products, EPD for plastics and EPD for steel[29].
Generic data is proxy data that can be used in a national context but will not be able to describe environmental impacts of a product sold by a specific building manufacturer (located in the country or abroad), unlike specific EPDs. In addition, in Europe, EPDs may use comparable Product Category Rules (PCRs) (if appropriate), company-specific individual foreground data, and partly different generic background data. The level of detail in generic and industry datasets can be very different [29].

4 Lifecycle Assessment within Cultural-E Context (LCA for PEBs)

Based on extensive research on literature and other projects, for building LCA, most applications consider 3 levels of assessments, which are:

- **Product level**: the single product
- **Functional system level**: consists of different components/products that fulfil a building function
- **Building level**: made by building constructions and systems as well as information on building operation.

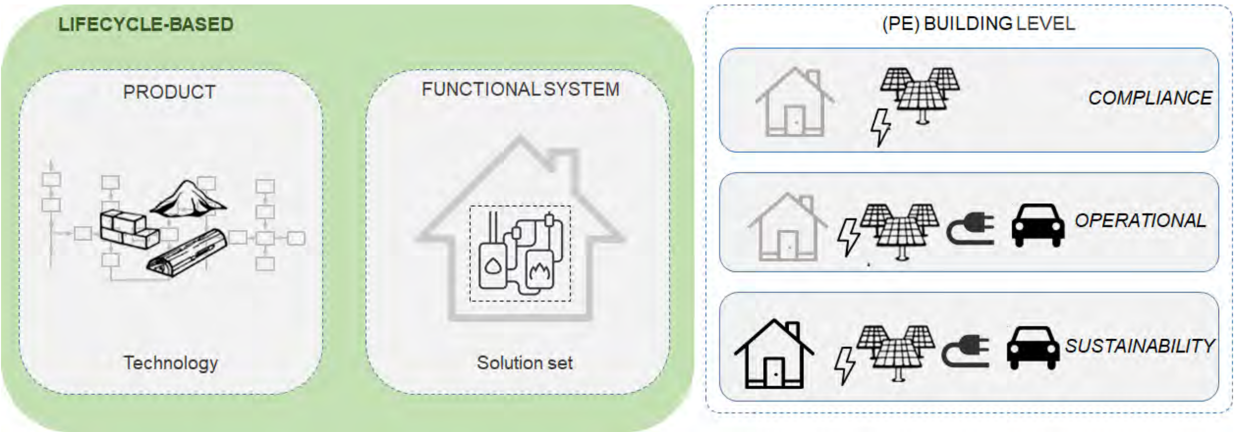

Figure 5: Overview of LCA analysis and assessment levels in Cultural-E.

In this work, the three LCA levels are translated here as following (see Figure 5):

- **LCA for technology components**: analysis of the single developed technology. Each component entails a component part, which in turn, the result of raw materials and transformation processes.
- **LCA for solution sets**: analysis of the set, which envisages building installations' elements. It includes heating, cooling, ventilation, TES, PV and distribution systems.
- **LCA for Plus Energy Buildings**: the analysis of the environmental performance of the designed PEB (carried out in other project's activities).

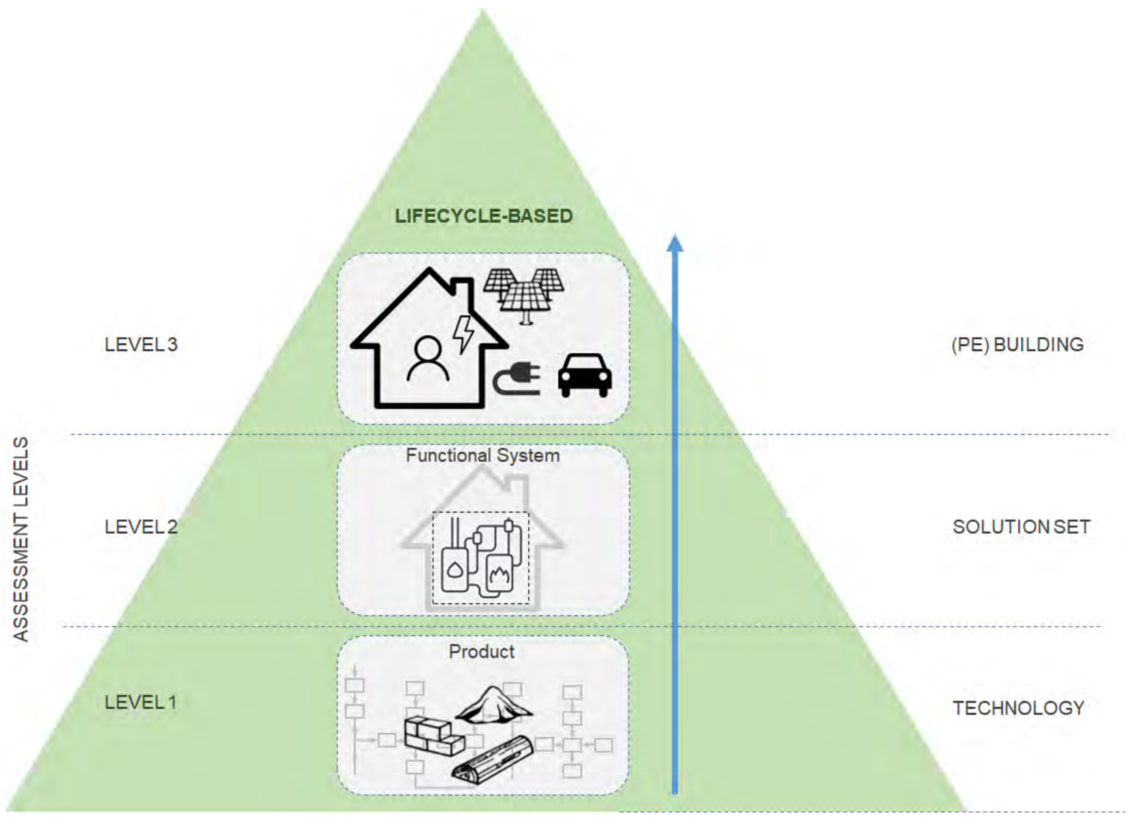

Figure 6 Sustainability Assessment Levels in Cultural-E.

The LCA analysis will be carried out through a bottom-up approach (see Figure 7), starting from the modelling of the single technology. Once provided all environmental information of needed products, solution sets can be modelled with products belonging to them. Finally, the sum of the information regarding all functional systems (i.e., solution set and building parts) will provide the LCA analysis on the building level.

In LCA analyses for Cultural-E, technologies are "decontextualized" from the building, its use destination, users, and their climate and cultural context. Consequently, the analyses are lifecycle-based, but with reference to product and the technology's service life. Such analyses serve for product and technologies developers, by providing environmental feedbacks on manufacturing and recyclability of products.

In contrast, analyses on solution set and PEB levels are carried out through an assessment, which should refer to a specific geographical and social context.

The PEBs' performance, according to the established PEB metrics, can be evaluated through 3 further assessment levels which cover different boundaries for operational energy (here called “*Physical boundaries*”) [35,36]. Further details about system boundaries for the assessment of PEBs are provided in Section 4.3.2.

Given the above, the following sections presents primarily the agreed guidelines and calculation methods for the LCA of technologies, solution sets, and PEBs.

4.1 LCA requirements and guidelines for technological components

Technological components of buildings fall under the category of products in the list of CEN/TC 350/WG 3 - *Products Level*, and as such the environmental assessment of this level is carried out based on EN 15804 norm [11].

4.1.1 Goal and scope of the assessment of technological components

The LCA of Cultural-E technological components is carried out with the goal to provide environmental profiles for the specific technologies, investigate therefore their environmental impacts and identifying environmental optimization potential. The LCA are not intended to be used in focused comparative assertions between products of the same or of similar characteristics (e.g.: no environmental impacts comparison will be carried out between two ceiling fan technologies).

The following technologies are investigated regarding their environmental impact:

1. The ceiling fan technology (NORDIC® ECO 120/48“) from Vortice
2. The active window system (AWS) from Eurofinestra
3. The packed heat pump system (VENTIVE-home system) from Ventive
4. The high-capacity hybrid storage (HCHS) from Brunel

In Cultural-E a technology of cloud-based House Management System (HMS) has been also developed. Environmental impacts for such a technology are in this work not provided and neglected within analyses on higher levels. In fact, the considered HMS is a software service and can contribute on the total environmental impacts. Still, it is more relevant from the LCA perspective, to analyze if HMS enhances effectively the building performance during its operation and reduces the environmental potential through a better management of building installations and services.

The LCA of the technological components is addressed to the project partners to whom the results are of interest for their further project activities, e.g.: to technology providers, technology integrators, demo-case designers and relevant parties. Work outcomes can be also addressed, in general, to all product developers interested in the assessment of similar technologies. Results can be also used from building developers for supporting decision making during building installations' planning.

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4.1.2 System boundaries of the assessment of technological components

The defined technological components which are chosen with the aim to contribute to the improvement of the energy performance in indoor environments of PEBs, are classified as building products and therefore the definition of the system boundary for the lifecycle assessment follows the EN 15804 norm [11]. Based on this and market available EPDs corresponding to the considered technological components (in chapter 4.2.1) a cradle-to-grave system boundary is considered which includes upstream, core and downstream processes. The lifecycle stages considered include: the product stage (modules A1-A3), the end-of-life (EoL) stage (modules C1-C4) as well as benefits and credits beyond the system boundary which result from the recycling scenarios during the end-of-life (module D). The lifecycle stages taken into consideration are shown in Figure 8 [11]:

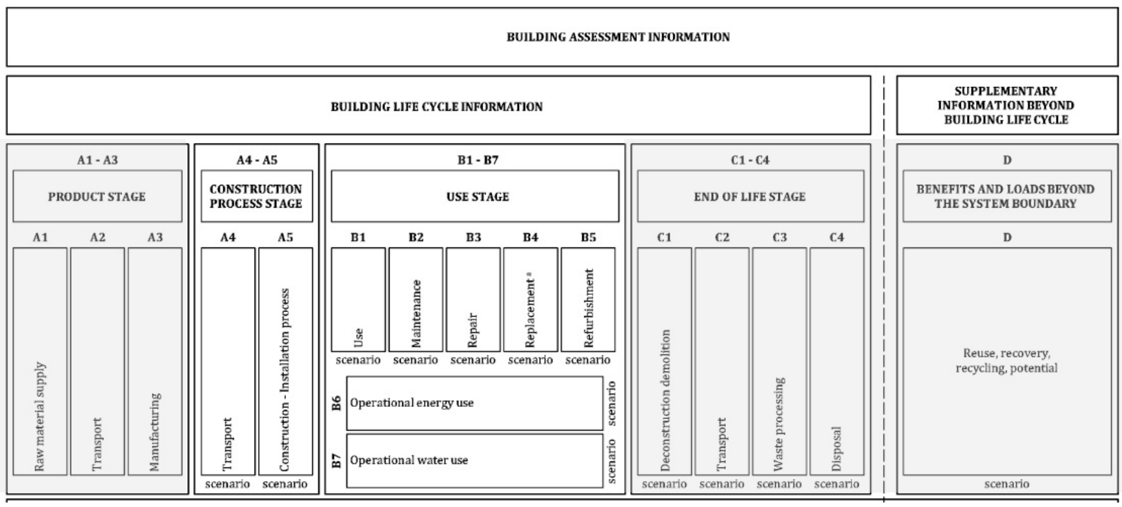

Figure 7. Life cycle stages taken into consideration for the lifecycle assessment of the technological components in a PEB based on EN 15804 [11].

For the lifecycle assessment of the technological components, all relevant material and energy flows must be recorded. This includes the provision of materials, components and technological assemblies with their assigned technical information, the manufacture information of preliminary products (as far as possible), as well as specific end-of-life scenarios for components which do not oblige to business-as-usual EoL routes or scenarios. The information to be recorded must come primarily from the technology providers and manufacturers.

4.1.3 Functional unit of the assessment of technological components

Based on the EN 15804 standard, the functional unit (FU) should be defined under consideration of the building context, in order to enable comparison between building products. For the definition of the FU of each technological component the EN 15804 [11], specific Product Category Rules (PCR) and technology relevant EPDs will be used as reference. The FU is specific for each technological component, and, as such, it is described in detail in the technology-dedicated following chapters.

4.1.4 Cut-off rules for the assessment of technological components

As stated in the PCR part A for all construction products, based on provision of information from the technology developers and manufacturers, available data on inputs and outputs must be included in the calculation [30]. For data gaps, conservative assumptions of average or generic data are considered.

All data regarding elementary input and output flows of the product system which are responsible for a minimum of 99 % of the resulting environmental impacts shall be included in the system, while the total sum of neglected input flows shall not exceed 5% of the energy and mass input. Cut-off rules apply to the LCA process of all technological components equally.

4.1.5 Impact categories for the assessment of technological components

The environmental impact of the technological components during their production and EoL stages, regarding the consumed resources are estimated in environmental impact categories. Based on EN 15804 +A2 Appendix C and as described in Section 3.6, the environmental impacts are calculated for the following impact categories (Table 2) [11]. These are chosen among the standard core indicators, depending on the work objective.

Table 2: Environmental core indicators for LCA analyses of Cultural-E technologies.

Indicator	Acronym	Unit
Global Warming Potential — total, fossil, biogenic, land use and land use change	GWP	kg CO2-eq.
Total use of renewable primary energy resources	PERT	MJ
Total use of non-renewable primary energy resource	PENRT	MJ

4.1.6 Data requirements for the assessment of technological components

For the creation of environmental models, data should be defined based on geographical, technical and time representativeness.

Data collection proceeds on the basis of primary data from the technology developers in the form of the BoM. The BoM is provided in an Excel sheet as a list of technological assemblies which are composed of smaller components for which the material, geographical origin and geometry information is assigned. Processing data in this form results in the definition of material and energy flows, which are recorded in the lifecycle inventory (LCI). The relevant flows are classified in:

- Characteristics of components: origin, material composition
- Geometry: surface in m², material thickness in mm, material mass in kg, etc.
- Estimate of the influence on the annual energy consumed for assembling (kWh) and in the use phase in kWh/a.

If the component is made by different sub-assemblies and component parts, these need to be specified as well as their materials and parts quantities.

A section of the data collection sheet (DCS) sent to the technology providers and used for collecting specific information on each technology in the form of BoM (Bill of Materials) in order to create the environmental models, is presented in Figure 9. The collected information through the DCS is used for the modelling process of the environmental models of the technological components in the environmental software GaBi ts [27]. The results from the LCA of the components are afterwards sent to the technology integrators and PEB developers for computational processing.

University of Stuttgart
Institute for Acoustics and Building Physics
Life Cycle Engineering GaBi

If the component is not produced in your facilities or the contained materials and masses are not known, please give information about the manufacturer and technical details about the product

Product	Component	Country of production	Project partner/ (research institute) is producer of component- YES/ NO	Further information on production process (eg: country, manufacturer, . . . other)	essential steps in the assembly process	Total Weight in kg	Material 1	Mass of Material 1 in kg	Material 1 cost (€/ kg)

Figure 8 Data Collection Sheet (DCS) used for collecting technology specific information.

The information contained in the BoM (from DCS) is applied in the environmental models for the input and output flows and matched with environmental databases. For the energy flows, generic datasets are chosen from the environmental database in accordance to the indicated origin of technological components. The results from the LCI phase of the lifecycle assessment method are used for further calculations in the Lifecycle Impact Assessment (LCIA) in the respective impact categories.

4.1.7 How to carry out LCA: Recap

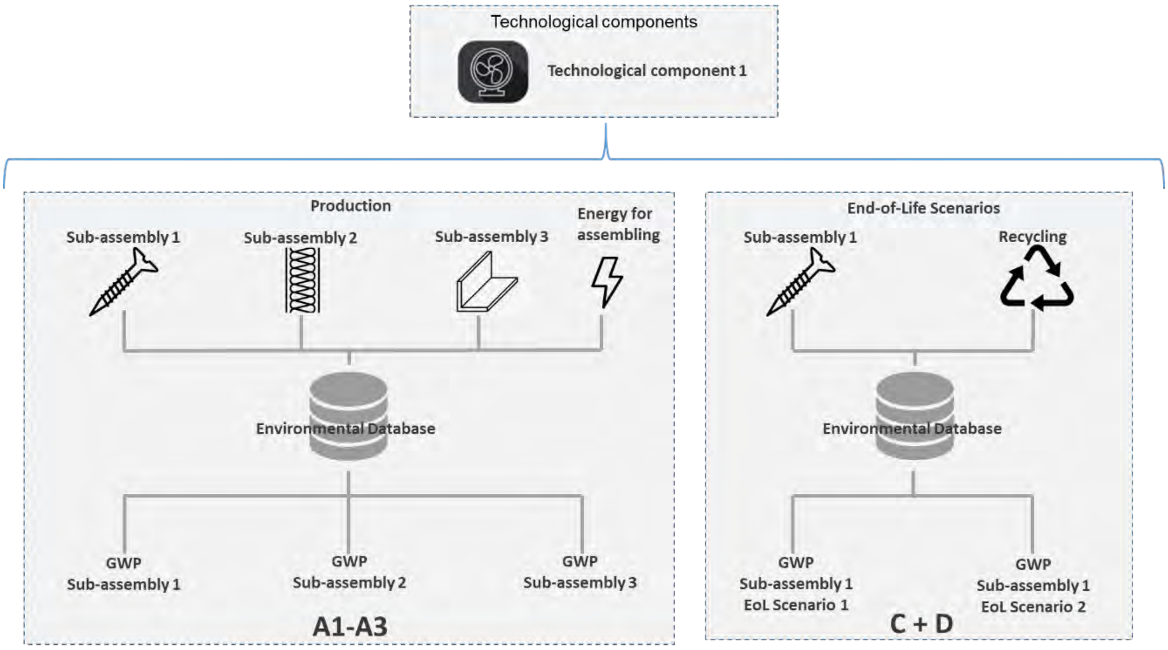

Figure 9 Method for carrying out the LCA of the technological components.

In order to carry out the LCA for technological components, data is processed as shown in Figure 10 and is based on the following steps:

- LCA requirements are used as a basis for the definition of the analysis framework in the beginning of each LCA process
- Information on the technological components is collected in the form of the BoM from partners through DCS
- Based on the information received, LCA requirements are specified and lay the foundation for the modelling process of the technological component in the environmental software GaBi ts [27]
- Collected information from the BoM is re-organized in technological sub-assemblies of same material composition
- For modelling the technological sub-assemblies in the environmental software GaBi ts, a screening process is done to select a proper environmental dataset, which is refers to be best match with the provided information.
    - o For the production stage (A1-A3) – manufacturing datasets are chosen
    - o For the end-of-life stage (C+D) – disposal datasets are chosen
- The sub-assemblies are then modelled through input of weight of the specific material in the chosen dataset
    - o Modelling of the production stage (A1-A3) and the end-of-life stage (C+D) is carried out separately in different modelling plans
- After the modelling is finished, a quality-check is carried out for the inconsistencies and information gaps together with technologies' developers
- With a finalized environmental model, the assessment is then carried out in GaBi ts for the relevant environmental indicators defined from the LCA expert
- Results are provided in the form of bar chart in the software, or can be exported in an excel sheet
    - o Results are exported for both the production stage (A1-A3) and the end-of-life stage (C+D)
- Results are reported and interpreted.

4.2 LCA requirements and guidelines for solution sets in PEBs

The environmental assessment of technological solution sets for buildings falls under the category of products as specified in CEN/TC 350/WG 3 - Products Level as well as CEN/TC 350/WG 1 - Environmental performance of buildings.

The LCA of solution-sets (Level 2) includes in fact both the environmental assessment of technological components (product level) as well as the operational performance of the PEB system. Therefore, a combined approach is required for this assessment level. The solution set is firstly analysed as group of components. Afterwards, it is located in a building with a specific climate and cultural contexts in order to investigate its performance during the operational phase [31]. The selected climate and cultural contexts are:

- *Mediterranean* (Italy – IT),
- *Continental* (Germany – DE),
- *Oceanic* (France– FR) and
- *Subarctic* (Norway– NO).

4.2.1 Goal and scope of the assessment of solution sets

The solution set is a system level, which is defined by grouping several components belonging to a building installation. All components are grouped as here following:

- Power Generator for Domestic Hot Water (DHW), space heating (SH) and cooling (SC) - PWG
- Thermal Energy Storage - TES
- SH/SC Distribution - DISTR
- Ventilation system – VEN
- Pipework, Valves, Circ. Pumps, Heat Exchanger - PIP
- Photovoltaics system - PV

The lifecycle assessment of solution sets is carried out to support the design and the choice of climate and cultural tailored solution sets. Possible goals of the lifecycle assessment can be also the following:

- Assessing the environmental impacts due to **the solution set as a whole**;
- Evaluating their **environmental impacts and positive performance** in different climate and cultural contexts and building types.
- Allowing the **comparison** among several alternatives designed for a specific climate and cultural context and building type.

4.2.2 System boundaries of the assessment of solution sets

The defined solution sets can be classified as **functional system** and a group of building products, for which the system boundary for the lifecycle assessment follows the EN 15804 standard rules [11]. Based on EN 15804 and market available EPDs corresponding to the considered technological components (in chapter 4.1.2) a cradle-to-grave system boundary is considered which includes upstream, core and downstream processes. The lifecycle stages taken into account, include: the product stage (modules A1-A3), the end-of-life (EoL) stage (C1-C4) as well as benefits and credits due to recycling (D) (see Figure 11) [11]:

To this purpose, all technological components and relevant material with their respective energy flows are recorded. As for the technology level, the data collection should include the provision of materials, components and technological assemblies with their assigned technical information, the manufacture information of preliminary products, as well as specific EoL scenarios for components, which do not follow common end-of-life routes, or scenarios. The information to be recorded come primarily from the technology providers and manufacturers. This information can be already provided for previous LCA analyses of technological components.

Solution sets can be assessed furthermore in a specific climate-cultural context: the yearly energy balance (use stage, B6 module[11]) of the overall system is calculated and included into the LCA system boundaries. Such results are derived through energy simulations. The user behavior can be also been implemented and included in the energy demand evaluation, by considering occupancy, plug loads and lightning usage.

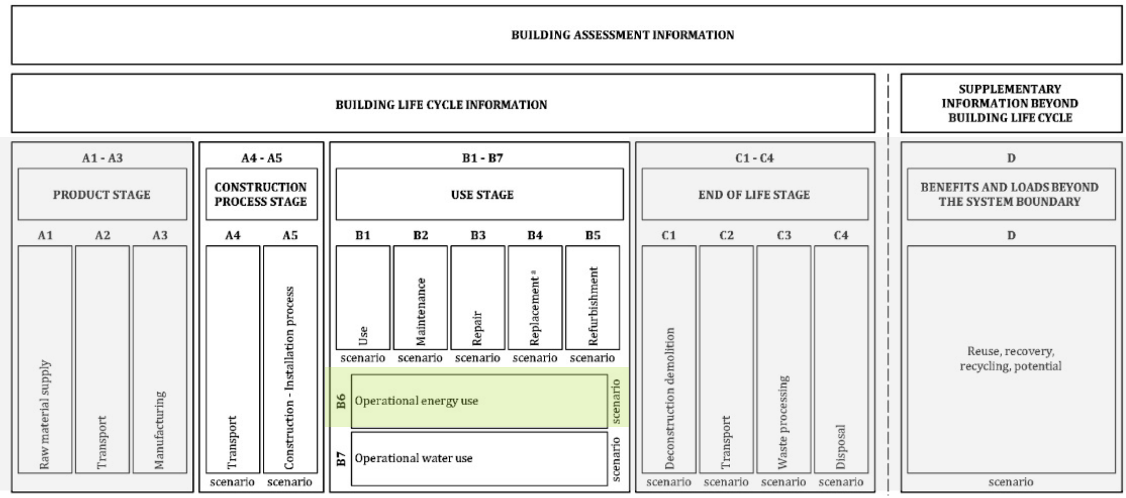

Figure 10. Life cycle stages taken into consideration for the lifecycle assessment of the technological components in a PEB based on EN 15804 [11].

4.2.3 Functional unit of the assessment of solution sets

Based on the EN 15804 standard, the functional unit (FU) should be defined by considering the building context, to enable building products comparison [11]. For the definition of the FU of each solution set, the goal of LCA analysis plays a relevant role.

- The environmental impacts can be assessed by considering the whole solution set as a unique **item**. This is suggested especially with analyses, which do not aim to relate the item to the building system.
- In analyses that aim to evaluate the share of environmental impacts of solution sets in a building context, the net surface (m²) is considered for the FU. The impacts can be included in a defined time frame, and as for sustainability assessment, it is suggested to refer to 1 year (Table 3).

Table 3: Solution sets. Functional unit definition.

Dimensions	**Specification**	**Unit**
Space	Area energy models	m² Net Floor Area (NFA)
Time	Year	Y
		*m² NFA*y*

4.2.4 Considered period of assessment

In this work, for solution sets, a 30 years' assessment period has been selected as a simplification. This choice solves issues related to technologies replacement modelling. Despite the novelty of some of the components, the ongoing technological developments, we assumed a service life at least equal to today's technology.

4.2.5 Cut-off rules for the assessment of solution sets

Cut-off rules for solution sets depend mainly on the assumptions provided on the technological level. These have been addressed in detail in Section 4.1.4.

Further cut-off rules may depend on the energy demand calculation, i.e. further assumptions within modelling for energy simulation, as well as assumption related to evaluation of the user-behavior.

4.2.6 Impact categories for the assessment of solution sets

The environmental impact of the technological components during their production and end-of-life stages regarding the consumed resources are estimated in environmental impact categories. Based on EN 15804 Appendix C [11] and as described in Section 3.6, the environmental impacts are calculated for the following impact categories (Table 4):

Table 4: Environmental core indicators according to [11].

Indicator	Acronym	Unit
Global warming Potential — total, fossil, biogenic, land use and land use change	GWP	kg CO2-eq.
Total use of renewable primary energy resources	PERT	MJ
Total use of non-renewable primary energy resource	PENRT	MJ

4.2.7 Data requirements for the assessment of solution sets

Data collection for solution sets follows conditions related to technologies and to the Bill of Materials (BoM) provided by solution sets' designers. These data should be defined according to geographical representativeness, technical representativeness as well as time representativeness.

To this purpose, an agreement on relevant in information to be collected occurred with solution sets' designers. This agreement aims also to facilitate the matching process between the information provided and the available environmental datasets (see Table 5).

As a basis of the assessment, generic datasets are chosen from the environmental database in accordance to the indicated specifications and component features. For, e.g., for the Cultural-E developed technologies, product-specific datasets are preferred.

Table 5: Data requirements for LCA of PEBs' solution sets. Installation components.

Component type	Specifications and feature		Total
PWG	PWG type (heat pump, boiler), Specify destination (heating, DHW)	• Power (in kW) • items	calculated
TES	• Storage Material • Storage Containment material • Insulation material • eventual information on Heating/Cooling buffer and its insulation	• Storage volume • Insulation material amount (estimated) • Buffer volume + estimation on insulation	
DISTR	Type (fan coils, radiators, etc)	• Items • (if fan coils) power • (if underfloor heating) surface	
VEN	Ventilation system description	Further information on capacity	
PIP	• Pipes material • insulation material for pipework	Ø (diameter), amount, long (ex. ø38mm x 10m)	
PV	Assumed: Average technology with battery, sized to provide a positive balance	Surface estimations	

Operational energy (B6 module [11]) is derived through building energy simulations and the total energy demand considered DHW, SH and SC. Accordingly, the useful thermal energy provided to the whole building - end users (DHW + SH + SC) is calculated (Qth_user), by considering all thermal losses. Qth_TE is the thermal energy generated by the generator (e.g. Qth_HP if the power generator is a heat pump) for DHW, SH and SC. Furthermore, energy usage consumption (Qel) of the single component has been derived. This includes appliances (APL), lighting (LGT), ventilation (VEN), Distribution (DIS) and auxiliary energy (aux) (see Table 6). The user behaviour is implemented in the different profiles for occupancy, plug loads and lightning usage. The climatic context is considered by using climatic data, and information related to the building envelopes.

Table 6: Data requirements for PEBs' solution sets. Operational phase.

Contributions for B6	Description
Qth_user	Thermal losses
Qel _ TE	Thermal energy generated for DHW, SH and SC
Qel_APL	Appliances
Qel_LGT	Lightning
Qel_VEN	Ventilation
Qel_DIS	Distribution
Qel_aux	Auxiliary energy
Total energy demand	Energy demand (positive)
PV pre-sizing	Estimation in terms of power and surface
PV credits	Energy credits (negative)
Energy balance	**Total energy demand + PV credits**

The derivation of the total energy demand allows a first preliminary sizing of PV modules in terms of power (kWp) and surface (m^2). Afterwards the estimated energy credits are summed to the derived total energy demand. When the calculated total energy balance is negative, the functional system produces more energy than its own demand. It is aimed therefore for PEBs.

The operational impacts are calculated, by taking into the account national electricity mixes and their respective impacts per kWh. This information can be provided by country-specific environmental databases as well as literature.

4.2.8 How to carry out LCA for solution sets: Recap

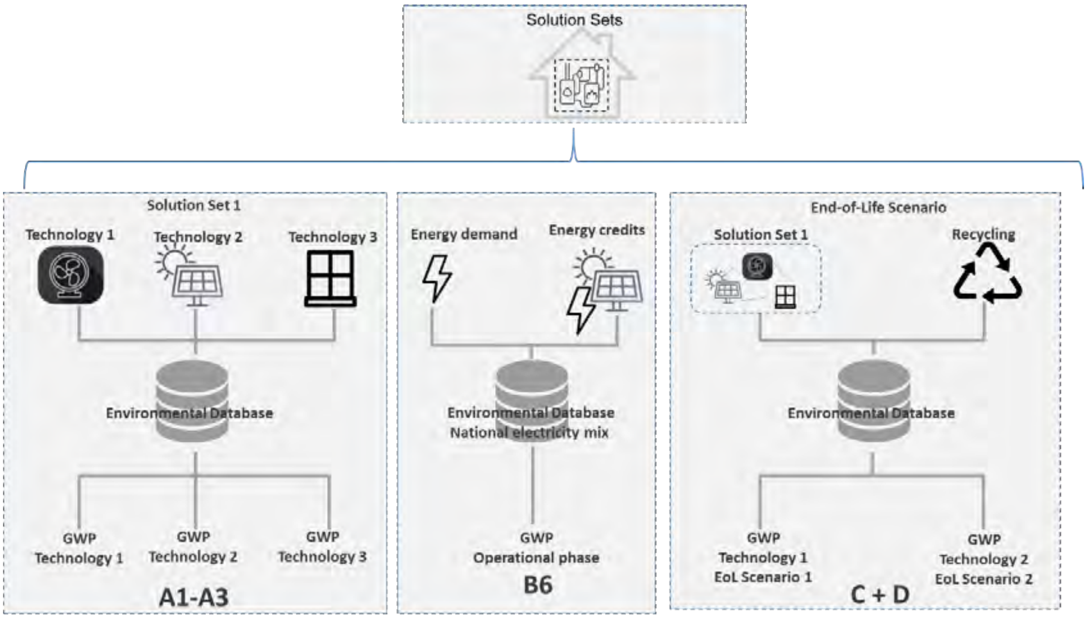

Figure 11 Method for carrying out the LCA of the solution sets.

In order to carry out the LCA for the solution sets, data is processed as shown in Figure 12 on the following steps:

- LCA requirements for solution sets are used as basis for the definition of the analysis framework in the beginning of each LCA
- The considered solution sets are defined through continuous collaboration with the partners
- Technological components types are defined according to their function within the building installations' system
- Information collected from partners initially on the individual technological components is used here as foundation
- Based on the defined technological specifications for the solution sets, environmental datasets are matched; an adaptation of the already modelled technologies in GaBi are carried out where necessary
- For modelling the solution sets, separate plans are created for the production stage (A1-A3) and the end-of-life stage (C+D)
- Building energy simulation are carried out, in which the solution set is located in a building belonging to a specific climate and cultural context. The final building energy demand is derived and compared with energy credits due to a PV system. Positive energy balances are checked.

- Modeling is done through an iterative process of checking continuously regarding data gaps and input of necessary information
- After the modelling is finished, a quality-check is carried out for the inconsistencies and information gaps
- With a finalized environmental model, the assessment is then carried out in a building LCA tool (GENERIS) [27] and relevant environmental indicators extracted.
- Results are displayed, presented and interpreted. They can entail:
    - Bar charts, for understanding each component's share from the total environmental impact
    - Pay-back time period visualization (see Section 4.4)

4.3 LCA requirements and guidelines for PEBs

Plus Energy Buildings correspond to the building level (CEN/TC 350/WG 1 - Environmental performance of buildings), for which the calculation methods for environmental sustainability assessment are based on EN 15978 [13].

4.3.1 Goal of assessment

The assessment aims to quantify the environmental performance of PEBs by recording and summarizing environmental information. The assessment results are intended to be used within Cultural-E to assess the designed demo cases.

PEB-LCA analyses should allow:

- **Analysis of a single PEB** in its climate and cultural context;
- **Comparison among PEBs**, in order to evaluate the positive energy performance, given a climate and cultural context;
- **Comparison between a PEB** and a standard building, which refers to **different energy performance** (e.g., nZEB) in a same climate and cultural context.

Objects, functional units and system boundaries should be selected in a proper way depending on the assessment goals.

4.3.1.1 Definition of the object of evaluation

A building is typically made of different constructions, which belongs to a building part. In this work, the building is defined by the following building parts[1]:

- Foundations
- External walls
- Ceilings
- Load-bearing elements (other than ceilings and external walls)
- Internal walls
- Roof
- Building Installations (→ provided solution set).

The constructive aspects need to be considered also with the operational performance, dictated by energy demand and credits.

Despite this object description can define already the system boundaries of the LCA analysis, according to the developed PEB metrics, object and its analysis can differ [32]. In PEB's metrics are in fact distinguished 3 assessment levels:

- *Compliance assessment* considers the building operation solely yearly. All installations are analyzed/compared regarding their energy consumption. The buildings are indirectly analyzed/compared, since the energy consumption values refer to the buildings' energy simulations.
- *Operative assessment* still neglects building constructions. Yearly final energy balances between delivered and exported energy calculated for each energy vector are measured.
- *Sustainability assessment* aims to evaluate/compare buildings including their construction, all derived activities including dismantling and recycling.

4.3.2 System boundaries

With regard on the PEBs' metrics and the 3 established PEB's assessment levels, it can be noticed that they define also 3 evaluation approaches of the B6 Module.

[1] The classification might need some tuning and variances, depending on the goal of the assessment. Despite the main goal of the assessment refers to the total building environmental impact, the building parts'classification can be also deemed useful to identify the areas, where there is an higher improvement potential or where appropriate measures are necessary to trade-off environmental performance with other requirements,

Consequently, they define also 3 building operation boundaries (called *"Physical boundaries" [32]* Figure 12).

- **Compliance assessments** focus on the single building level and quantify yearly balances under consideration of heating, cooling, DHW, ventilation, lightning and auxiliary energy.
- **Operative assessments** include all previous entries together with plug loads and, depending on building functionalities and areas, electric vehicles' charging.
- **Sustainability assessment** includes the total operational energy as in operative assessment, added with embodied energy. The assessment is here provided over the whole building lifespan.

The first two approaches cannot be classified as life-cycle based. Since in this work aims to "cradle-to-grave" analyses (lifecycle based), the PEB-LCA will follow uniquely sustainability assessment approach, where the considered lifecycle modules are manufacturing (module A1-A3), operation (B), disposal (C3-C4) and credits from recycling or re-use (D) [13]. Within the building operation, energy demand (B6) is considered together with renovations activities (B4-B5).

Compliance and operational approaches will be here not intended for LCA analyses.

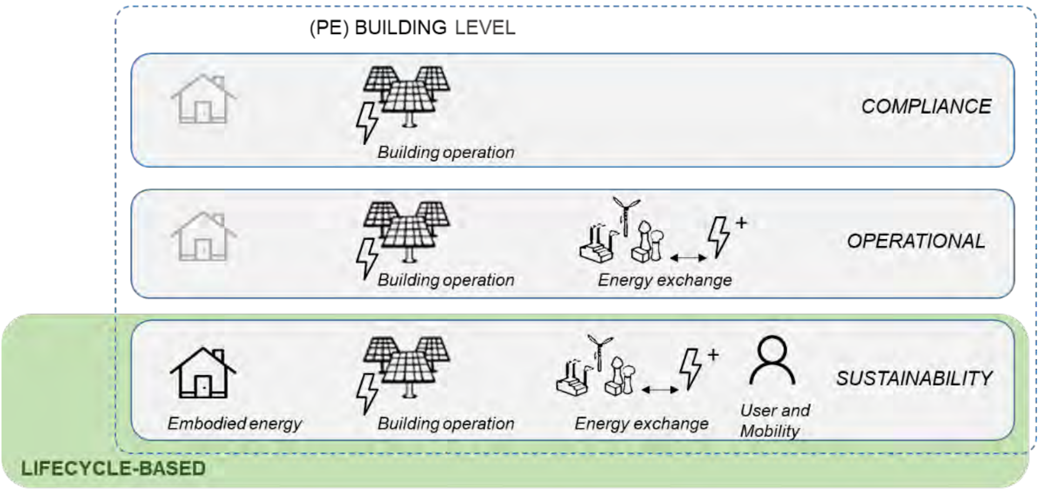

Figure 12: Cultural-E 3-levels of assessment for PEBs.

4.3.3 Functional equivalent and functional unit

The functional equivalent considered for studies which focus on the assessment of PEBs, is a PEB used for residence, operating on an energy efficient standard (Plus Energy standard), delivering a negative annual primary energy demand and a negative annual final energy demand, within the required service life [33]. Climate and cultural context are included. Therefore, each of the analyzed demo cases has a different functional equivalent.

The functional unit of a building represents a quantitative description of the performance requirements that the building system fulfils.

Following the recommendation of Souza [34], the net floor area was chosen to represent the analyzed space (Table 7). The main service of the building can be represented by the use destinations, e.g., dwelling. For a higher representativeness of the FU (optional), the latter can include the inhabitant.

The period of the analysis can be the whole building service life. If the LCA analysis aims to provide benchmarks for building on the yearly scale, FU will include a yearly distribution as well. Details on the considered assessment period are provided in Section 4.3.4. In addition to this, a quality standard in terms of energy performance and IEQ should be declared, in order to provide consistent buildings comparisons.

Table 7: Sustainability assessment. Functional unit definition.

Dimensions	Specification	Unit
Space	Area energy models	m² Net Floor Area (NFA)
Time	Service Life/Year	30ys / 1y
Service	Occupancy district	Inhabitant (Inhabit) - optional
		*m² NFA*y(*Inhabit)*

4.3.4 Considered period of assessment

The sustainability environmental assessment is carried out based on a selected reference study period. If the LCA aims to analyze a single building, the period of assessment can coincide with the building service life. Building service life is the period of time in which a building is in use and can affect the activities required to maintain, repair and replace building materials and systems. It can also affect the extent of recurrent embodied energy required over the building's life. For this work, 30 years' assessment has been selected as a simplification. This choice solves three main issues:

- Different buildings' service life in several contexts. A common and sufficient period for environmental impacts assessment is established.
- PEBs' technologies and solution sets replacement modelling. Due to the novelty of such components, the ongoing technological developments and their relevance in the overall LCA, the assumption of replacement with the today's technology may leads to question the results' transparency.
- See the building performance in the timeline dictated by the Paris Agreement, which requests the achievement a carbon neutral society by 2050.

Materials and components with service life lower than 30 years are still subjected to a replacement occurrence, as described by the following formula:

$$N_R(j) = E\left[\left(\frac{ReqSL}{ESL(j)}\right) - 1\right]$$

where:

E [ReqSL/ESL(j)] function according to which the ReqSL/ESL(j) function is rounded up to an integer;

ESL(j) expected useful life of the product j;

NR(j)	replacement rate for product j;
ReqSL	reference service life of the building or study period

4.3.5 Cut-off rules for PEBs assessment

Building LCA analyses can be a long and time-consuming process. This is due to the multitudes of elements, materials, and information to be collected. However, ISO standards allow cut-offs, which enables LCA practitioners to conduct LCA without having to model 100% of the product system[14]. For building LCA analyses, the cut-off criteria refer to the omission of non-relevant life cycle stages, activity types, specific processes and products and elementary flows from the system model. Cut-off rules should be set up depending on the goal of the analyses and also depending the LCA analysis type during planning process [15].

Building Screening LCA [15] can be carried out during the early design, with few but relevant information. A simplified LCA considers most of the building parts but can have issues in data quality [15]. Since it can be carried out before the building construction process, some quantities can differ in comparison with the one provided at the end of the construction process (Complete LCA). Here as follows in Table 8, recommendations for building constructions and elements selected and excluded in the three LCA types are presented. Red-marked cells refers to necessary information, orange refers to information to be possibly included, green for information that can be excluded.

Table 8: Applied Cut-off for three LCA analysis types. Red-marked cells refers to necessary information, Orange refers to information to be possibly included, green for information that can be excluded.

	Screening LCA	Simplified LCA	Complete LCA	Comments
Foundation				Data quality can differ depending on LCA analysis and information availability
Preliminary works				Not usually considered
External wall				Data quality can differ depending on LCA analysis and information availability
Floors				Data quality can differ depending on LCA analysis and information availability
Interior walls				Data quality can differ depending on LCA analysis and information availability
Roof				Data quality can differ depending on LCA analysis and information availability
Heating system				Data quality can differ depending on LCA analysis and information availability
Ventilation system				Data quality can differ depending on LCA analysis and information availability
Cooling system				Data quality can differ depending on LCA analysis and information availability
PV systems				To be prioritized in PEBs
Electric devices				Information not always available or comprehensive.
Communication/security devices				In some analyses included in electric devices
Building automation / Smart building elements				In some analyses included in electric devices
Others(e.g. mobility, infrastructures, interior equipment)				Not usually considered or out of scope in respect to the building object.

In building systems, constructions with concrete and steel elements are characterized by higher environmental potential [35], and, therefore, require particular attention. When the information is delivered, exterior works and foundation can be included. As for the most high-performance energy buildings, in PEBs, due to their wide surfaces, PV systems can be relevant for the overall environmental performance [36,37]. For this reason, they are in this context relevant. In Cultural-E, the demo cases are provided with House Management Systems (HMS). In most of building LCA, such elements can be excluded since they are cloud-based systems. Most of their impacts are related to electronics components (e.g. sensors and controllers) and therefore included in the assessment of electronic devices. While their relevance is growing in field of building LCA, in this specific work their impact is still deemed lower than other appliances. Their inclusion is there only suggested for results enhancement and for the evaluation of effectiveness in terms of derived energy savings. As for all buildings, heating, cooling and ventilation are considered for the evaluation of the operational impacts of PEBs.

4.3.6 Data requirements and quantification of the building and its life cycle

The evaluation of quantities to input into building lifecycle modelling can be provided through information exchange between all actors involved in the building planning and by researching environmental information of building products, if possible, product-specific (such as EPDs) directly from product developers. This, even if more time consuming, may be important, especially when the used products are innovative and cannot be matched with generic datasets.

Figure 13 below showed the collected information the respective information provider, based on the conducted activities.

- The information regarding embodied impacts is coming from product developers and planners. Technology developers (WP3, blue in Figure 13) deliver details on technologies, while demo cases designers (WP6, yellow in Figure 13) provide building and building constructions' design specification.
- Demo cases designers (WP6) can prepare documentation about the whole construction process, e.g. material transport details and required energy in the construction site. This lifecycle phase is however in a first instance not included in the system boundaries.
- Building use phase gathers information regarding climate and cultural differences in energy use in domestic buildings including user behaviors from 2CAP/ Atlas tool [38] (WP2, grey in Figure 13) together with PEB energy simulation (WP4, red in Figure 13) can provide total energy use.

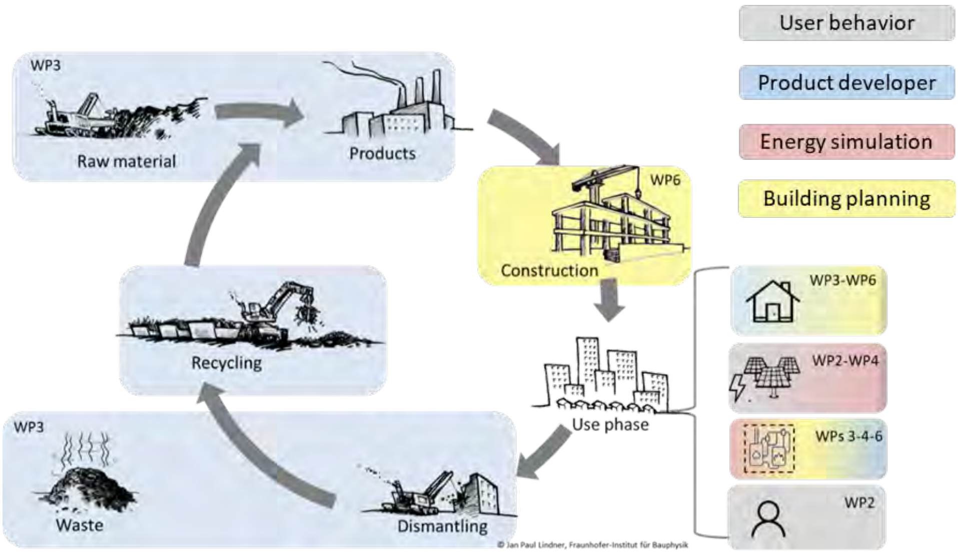

Figure 13: Data collection and quantification over the building lifecycle in Cultural-E.

4.3.6.1 Data collection for Building LCA

For the whole consortium and especially for demo cases' designer a datasheet is prepared aimed for the collection of building constructions' information (see also Figure 14).

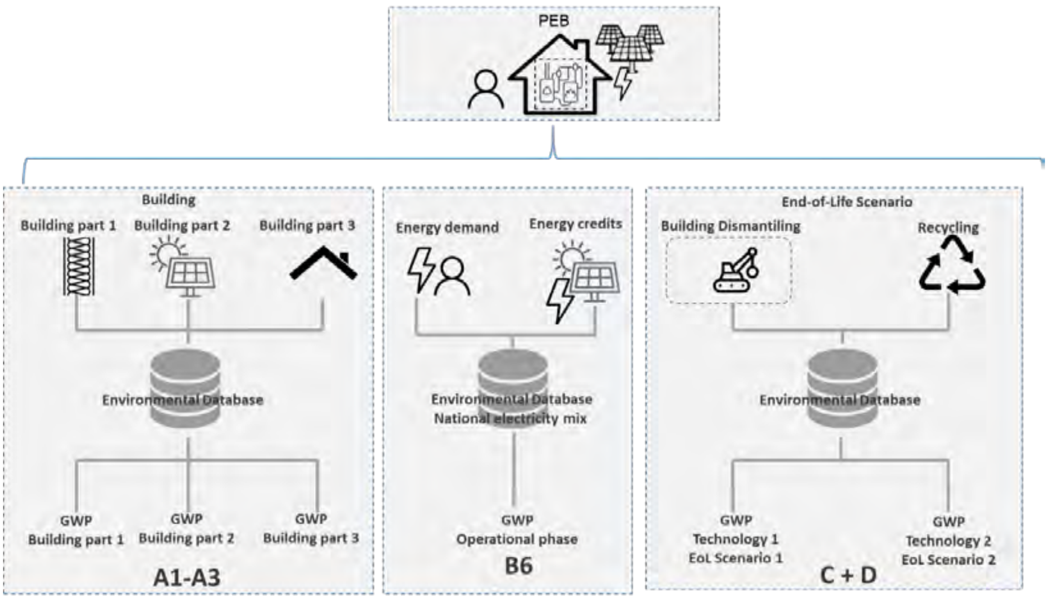

Figure 14: Data collection for Building LCA.

The Excel documents presents 6 different sheets to be filled out. Each of them presents information on a specific building part (foundations, external walls, ceilings, internal walls, roof, and installations). Each building part can present one or more constructions. Each construction should therefore specify (e.g., External wall southwest – Abbreviation EW SW).

For each construction are required:

- Construction's Surface
- Materials' list (from inside to outside the building)
- Layers' thickness
- Density (if available)
- Layers' surfaces
- Lifespan

Table 9: Data collection for Building LCA. Data required.

Demo Case Nation - Building 1						
	Construction name	**External Wall Southwest**				
	Abbreviation	EW SW				
	Building part	External walls				
	Quantity:	**120.00**		**m2**		
	INSIDE					
Nr.	Material	Environmental Datasets	Layer thickness [mm]	Density [kg/m3]	Surface [m2]	Lifespan
1	Material 1	USTUTT specified for each material and agreed with demo case developers	300	10	100	50
2	Material 2		30	40	100	20
3	Material 3		5	3	100	15
4	Opening		60	missing	20	15
5						
6						
7						
	SUM					
	OUTSIDE					

Each building part can present one or more constructions. Each construction should therefore specify (e.g., External wall southwest – Abbreviation EW SW).

Information on building operation is while derived, as for solutions sets, through building energy simulation.

4.3.6.2 Type of datasets for the assessment

Depending on environmental databases and product information, the LCA of PEBs should refer both generic and specific environmental information. Each information provided regarding materials is matched with a product specific or generic dataset. The considered generic environmental databases are ÖKOBAUDAT in the German context [39], and ESUCO in the other European countries.

Product specific datasets are while derived from EPDs or previous GaBi models [27] imported into the SBA Tool.

As for solution sets, the operational impacts are calculated, by taking into the account national electricity mixes and their respective impacts per kWh.

4.3.6.3 Building lifecycle modelling and impact assessment with SBA Tools

The building model and the resulting sustainability impact assessment of a system should not only consider individual processes or phases, such as operation. A holistic approach should also include the direct energy and the material flows, as well as their associated energy and environmental impacts over the entire life cycle of a system. The use of life cycle assessment (LCA) tools and integrated sustainable building assessment (SBA) provides an important basis for feedback on planning decisions at a conceptual level regarding their impact on the entire life cycle of a building, to ensure compliance with the targeted sustainability performance. Various SBA tools have been developed alongside the LCA methodology [40]. Their main functions adhere to the evaluation of environmental performance for certification purposes, and address environmental comparison of design alternatives.

Presented here is the modelling approach required by the SBA tool GENERIS® of Fraunhofer Institute for Building Physics (IBP) [41]. Please notice that the tool has been adapted according to the German context as default, but evaluation for international context and environmental certification is allowed, for instance with the inclusion of quantities are entries according to standards of different countries.

Within the design of a building, modelling can be divided in five main steps. The following information should be provided:

1. A **detailed description** - information about database, evaluation profile, keywords, etc.
2. **Functional units** - list of the available functional units according to the selected DIN standard.
3. **Use** - information about energy consumption during operational phase and sources of energy.
4. **Constructions** - list of the constructions belonging to the building
5. **Construction** - a single construction with its respective layer can be assigned.

Building Description

In this section the following details are entered:

1. Title
2. Database (i.e., select "Use current Ökobau.dat" to use the current German database)
3. Element category, selected by a dropdown list
4. "Keywords, hierarchy": write or find keywords by dropdown list.
5. Functional Units system (according to the German standard DIN 277 or DIN 283)
6. Language, selected by a dropdown list

Functional units

The selection of a DIN standard brings you to a list of functional units. With the selection of DIN 277 standards as default, the available functional units based on geometry and usage (net area, usage area, area for technical services, etc.) are provided (Figure 15).

Description | Functional units | Use | Constructions | Construction

Filter

Name	Title	Quantity	Unit
BGF	Brutto-Grundfläche	0.00	m2
NGF	Netto-Grundfläche	100.00	m2
NF	Nutzfläche	0.00	m2
TF	Technische Funktionsfläche	0.00	m2
VF	Verkehrsfläche	0.00	m2
KGF	Konstruktions-Grundfläche	0.00	m2
BRI	Brutto-Rauminhalt	150.00	m3
NRI	Netto-Rauminhalt	0.00	m3
KRI	Konstruktions-Rauminhalt	0.00	m3

Figure 15: Functional units according to DIN 277 in GENERIS® [41].

If your standard is DIN 283, the available functional units are the room areas (Figure 16).

Description | Functional units | Use | Constructions | Construction

Filter

Name	Title	Quantity	Unit
GSF	Grundstücksfläche.	0.00	m2
WF	4.1 Wohnflächen	25.00	m2
Wohn- und Schlafräume		75.00	m2
Küchen		10.00	m2
Nebenräume		0.00	m2
NF	4.2 Nutzfächen	0.00	m2
Wirtschaftsräume		0.00	m2
Gewerbliche Räume		0.00	m2

Figure 16: Functional units according to DIN 287 in GENERIS® [41].

For buildings not located in Germany, GENERIS® allows the creation of packages of further functional units, which can be related to different country-specific standards: this level of flexibility can solve issues due to a missing harmonization among current standards in the considered Cultural-E demo cases.

Despite the cultural differences, the established functional units, i.e., treated floor area (TFA) and net floor area (NFA), present definitions, which benefits from their harmonization over the European context. TFA is defined by Passive House Planning Package (PHPP), while NFA definition can be found in EN 15221-6. In this regard, for example, the German DIN 277 is now aligned to the EN 15221-6 and therefore selected for the analyses.

Use phase information

In “Use” you can enter all necessary information about building use phase.

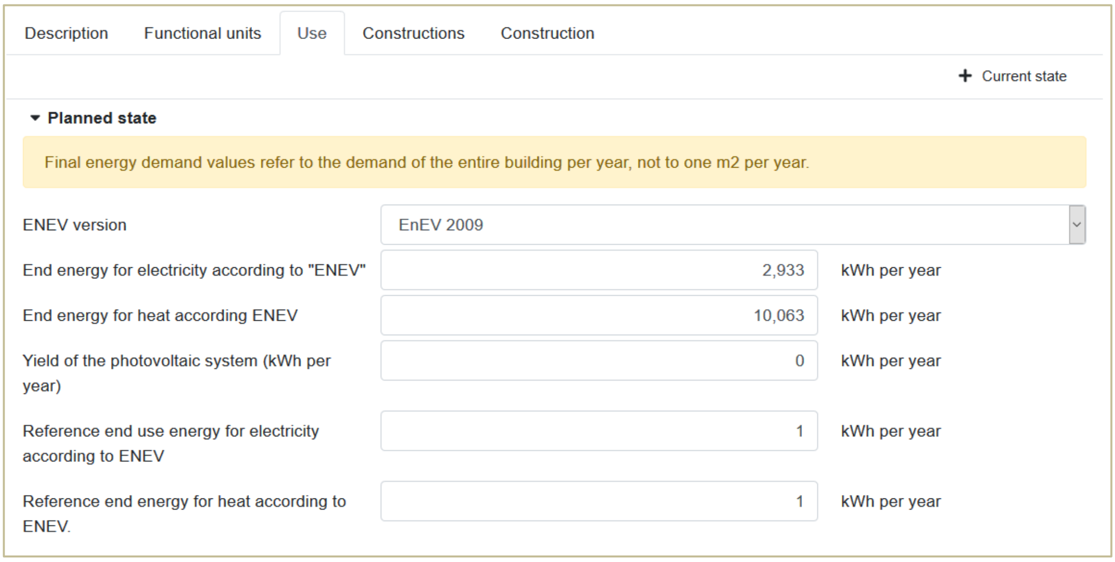

Figure 17: Use-Phase information required in GENERIS®.

In this section, the following inputs are asked for (Figure 17).

1. EnEV version (necessary for evaluation in the German context. These can overlap further energy policies in the European context)
2. End energy for electricity according to EnEV
3. End energy for heat according to EnEV
4. Yield of photovoltaic system
5. Reference values for both electricity and heat energy according to the energy policy

All values refer to the energy in kWh of the entire building per year.

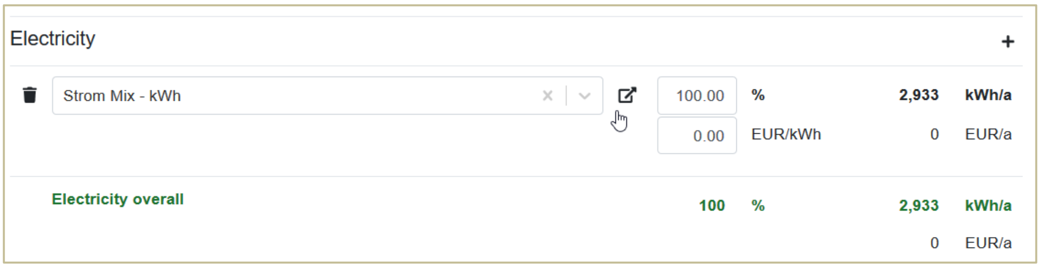

Figure 18: Energy sources attribution in GENERIS® [41].

Once the values of End-energy for electricity and heat are entered, it is necessary to assign the respective energy sources (Figure 18).

By clicking next to “Electricity”, “Heating” or “District heating” a new field is enabled. In this instant, the following steps are:

1. To select the desired Process representing the energy production either from the dropdown list or by writing the name, and
2. To specify in percentage terms the coverage planned for the selected Process of the chosen energy production.

Constructions

The building constructions can be provided, by entering the following information (Figure 19):

1. Construction name
2. Category name, selected by the drop-down list
3. Cost group, selected by the drop-down list
4. Service life of the construction
5. Quantity and unit

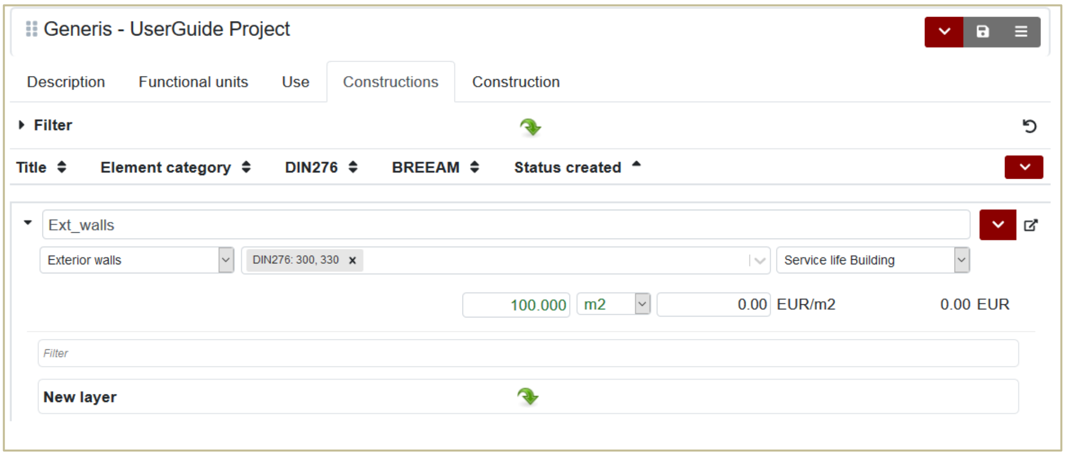

Figure 19: Construction attribution in GENERIS® [41].

Construction layers are afterwards assigned.

With the addition of a layer, the following information should be entered (Figure 20).

1. Title
2. Material flow direction (In, Out, In/Out)
3. Quantity
4. Process
5. End of Life information

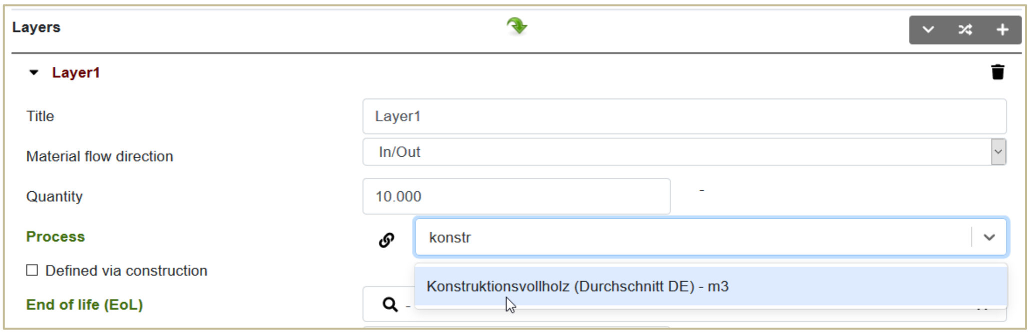

Figure 20: Layer definition in GENERIS®.

4.3.7 Environmental indicators and impact categories

Environmental impact categories and indicators to be assessed are chosen with regard to their current relevance and with regard to provisions in the existing European standards and objectives [11,13]. The life cycle impact assessment (LCIA) is provided for the following environmental impact categories as defined in EN 15804+A2:

- Climate Change with calculation of Global Warming Potential total (GWP 100) in [kg CO2-Equiv.]

Furthermore, the following environmental indicators are considered to complete the overall assessment:

- Primary energy from non-renewable resources (net calorific value) in [MJ]
- Primary energy from renewable resources (net calorific value) in [MJ]

The choice on the environmental indicators considers the focus of Cultural-E in carbon footprint and energy reduction issues.

For the impact assessment, the characterization model of the Centre for Milieukunde in Leiden (CML) is considered and included in the used Building LCA Tool.

4.4 Environmental payback period evaluation for solution sets and PEBs

As shown in preliminary LCA analyses conducted in the context of Cultural-E, PV modules can contribute significantly to the total assessed embodied impact. Their environmental performance can be therefore questionable. On the other hand, they are source of renewable energy during the whole functional system and building system lifespan. In terms of environmental impacts, they allow credits by avoiding emissions related to energy consumption coming from non-renewable sources. Applying an economic analogy, PV systems can help to “pay-back” an initial environmental climate “investment”.

The “***payback period***” (see Figure 21) is defined as the time required recouping the embodied energy and impacts (EI_{tot}) and to reach the break-even point can be estimated, as well as the total yearly impacts and energy savings (OI_y) during the building operation.

PB periods can be calculated by assuming a static or variable electricity mix.

4.4.1 Static environmental payback period

When the electricity mix is assumed constant over the considered analysis period, the curve has a linear trend (see *FIGURE 21*) and the PB period is calculated as following (Formula 1):

$$PB_{env}\,[y] = y_{today} + \frac{EI_{tot}[kg\ emissions\ eq]}{OI_y\left[\frac{kg\ emissions\ eq}{y}\right]} \qquad (1)$$

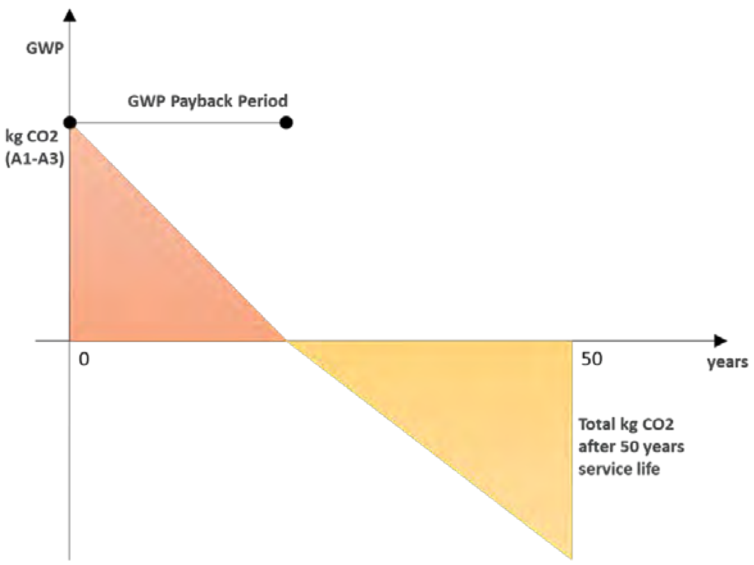

FIGURE 21: PAYBACK PERIOD OF ENVIRONMENTAL IMPACTS.

This assumption, even if used mostly for the evaluation of the total operational energy and impact saving, is not realistic nor suggested for the estimation of the PB time because not conservative (see Formula 1). In addition to this, in building LCA, using historical data for energy production mix does not reflect the variation and the improvements that European countries are committed to in the coming years. As a result, transparency of LCA results may be questioned.

4.4.1.1 Dynamic environmental payback periods based on EU Reference Scenarios

With the aim of a better investigation on building energy balances and their respective environmental impacts, for the planned Cultural-E demo cases, forecasts on national electricity mix dynamics are a suggested way.

The EU Reference Scenario allows for analyses on long-term economic, energy, climate and transport outlook, based on the policy framework in place in 2020. According to the suggestion of European Union, is therefore EU Reference Scenario selected as baseline [42], and country-specification are considered for the different contexts (see Figure 22).

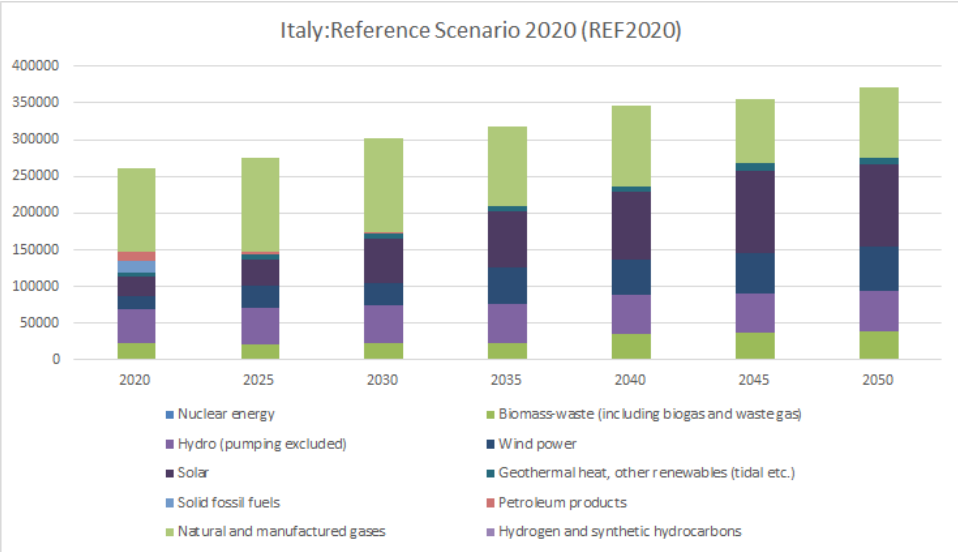

Figure 22: Electricity mix scenarios for Italy, according to EU Reference Scenario 2020 [42].

This variation can be also translated into a variation of impact intensity of the national electricity mix. For the dynamic payback period evaluation, the impact intensity variation has been expressed through a discount rate, which is estimated on a 5-years' basis, as for the electricity mix scenarios (Table 10). These estimates the decrease CO2 emissions of the national energy mix (in the example, Italian energy mix is considered), which, in turn, is updated every 5 years. Within each 5-years' time range, a linear variation of the CO2 intensity is then assumed. As shown in this fictive example, dynamic assessments are more conservative and, as a further advantage, more realistic.

Table 10: Estimation of electricity mix scenarios and CO2 intensity for Italy.

IT			
	Discount Factor	CO2 intensity Electricity mix	Building GWP trend [kg CO2 eq.]
2022		0.285	**100.00**
2025	-0.041	0.273	83.32
2030	-0.119	0.241	58.84
2035	-0.150	0.204	38.04
2040	-0.086	0.187	19.02
2045	-0.098	0.169	1.86
2050	-0.022	0.165	-14.92
		PB (dynamic) in year	**2046**
		PB (static) in year	**2039**

In the overall, although life cycle assessment offers insights into the long-term value of our building stock, modelling the whole service life of a building with absolute certainty is not feasible.

In many fields, scenario-based analyses proved to be a valid strategy [43]. A scenario in LCA studies is a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future [44]. Therefore, they can be included also in Solution sets and PEBs environmental impact assessments.

5 LCA specifications and results for the Cultural-E technologies

Due to the different nature of the developed technological components in Cultural-E, which differ from each other in terms of geometrical scale, function and technical performance, the establishment of a product-specific LCA set up is necessary. LCA requirements can differ in each product in terms of:

- Technology description
- Function and functional unit
- Reference service life
- Data quality

Here following, an overview on LCA set up and calculation methods is provided for the developed technologies together with necessary clarifications.

ANNEX II – Summary of LCA results resumes all LCA specifications and results for the technological components taken into account in Cultural-E in a structured and comprehensive form.

5.1 Eurofinestra Active Window System

Figure 23: Active window System prototype.

The AWS technology represents the transformation of the traditional window into an active building element that contributes to the energy efficiency and indoor air quality, and is able to cooperate within a broader indoor air quality control strategy (Figure 23). Within this system are incorporated the following technological pillars:

- **The modular wood frame system**
  Customization of thermal transmittance (U_W) according to specific climate-configurations is possible
- **An integrated decentralized ventilation device**
  It is available in two configurations:
    a. Surface-mounted trickle vents are integrated into the frame to allow natural ventilation (Figure 24)

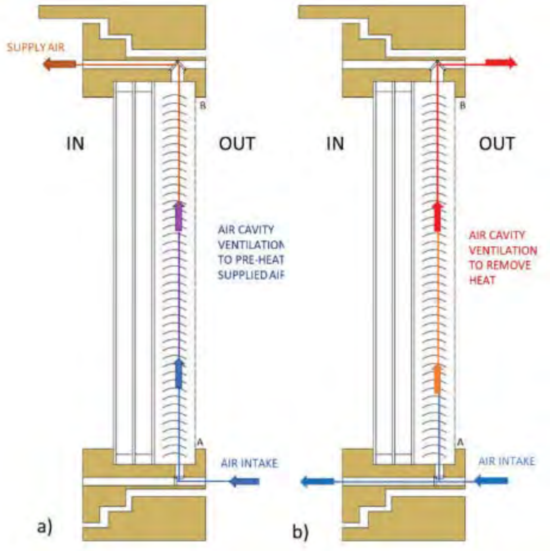

Figure 24: AWS configuration with trickle vents in window frame.

    b. A compact mechanical ventilation unit is integrated with heat recovery function (Figure 25)

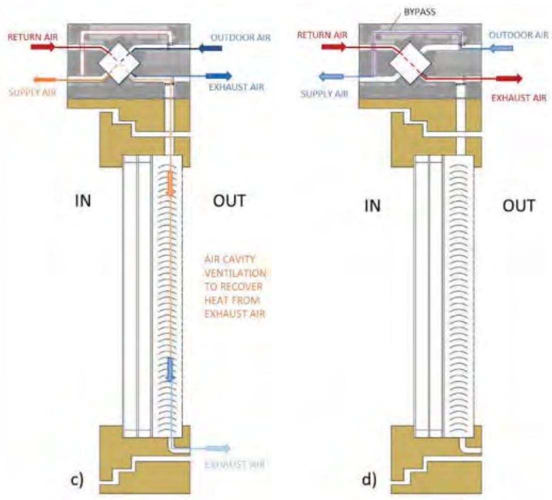

Figure 25: AWS configuration with mechanical ventilation unit installed in the frame.

- **A movable adaptive shading system – venetian blinds**
  The venetian blinds are located within a chamber, in front of the insulating glass pane in the exterior side of the window and protected from a second glass pane which can be opened up for maintenance. Through this chamber heat recovery from exhaust air and the heating effect of the fresh air entering the system are allowed.

5.1.1 LCA specifications

Table 11: LCA specifications for AWS.

AWS - LCA Specifications (based on ISO 14044)	
Goal	Environmental profile assessment of AWS systems. The LCA of this technology is addressed to the project partners, e.g.: to technology developers, demo-case coordinators and relevant parties. The results will be disclosed to public while LCI is confidential. Product specific comparative assertions are not intended within the assessment.
FU	1 m² window
RSL	30 years
System boundary	Cradle-to-grave system boundary based on EN 15804 2020. - the product stage (modules A1-A3), - EoL stage (modules C1-C4) - benefits and loads beyond the system boundary (module D)
Cut-off criteria	All data regarding elementary input and output flows of the product system, which are responsible for a minimum of 99 % of the resulting environmental impacts, shall be included in the system. In terms of mass, 95 % of the total mass shall be included in the system (PCR part A)
Impact categories	- Global Warming Potential - GWP in kg. CO2 eq. - Total use of renewable primary energy resources - PERT in MJ - Total use of non-renewable primary energy resources - PENRT in MJ
Environmental database	GaBi ts version 10 of the software, using the professional extended GaBi database SP40 [27].
Data requirements	- Characteristics of components: origin, material composition - Geometry: surface in m², material thickness in mm, material mass in kg, etc. - Estimate of the influence on the annual energy demand in the utilization phase in kWh/a.

Assumptions	Assumptions for the EoL stage based on available EPDs for window products and according to default values specified in EN 17213 Metals → C3 - central sorting of mixed construction waste. Recycling of metals; crediting for primary material use will be taken into account in D module Wood → C3 - municipal incineration with energy recovery and crediting for electricity and heat production Plastic → C3 - municipal incineration with energy recovery; C4 - landfilling of ashes from incineration

5.1.2 LCA results

Comprehensive results from the LCIA are attached in Annex II.A. Active window system. Here below results for the indicator GWP and PENRT are presented and discussed. With regard to the AWS environmental profile, it can be noticed that most of its potentials lies in the Ventilation Machine and the Shading systems (Figure 26 Figure 27 Figure 28 Figure 29).

The ventilation machine (Figure 30) entails electronics and plastic parts, which affects strongly the final impact assessment. Shading systems (Figure 31) are made by steel, aluminum and PVC parts, which belongs to shadings blinds and auxiliary elements (profiles).

However, both AWS's sub-components are ready-to be assembled and not manufactured from the Eurofinestra technology developer. In the overall, the AWS system and the sub-components and parts manufactured by Eurofinestra have a minor contribution on the environmental performance. As a suggestion for future improvements, technology developers are therefore in this context recommended to find better ventilation machines and shading systems alternatives, which may have a reduced environmental impact.

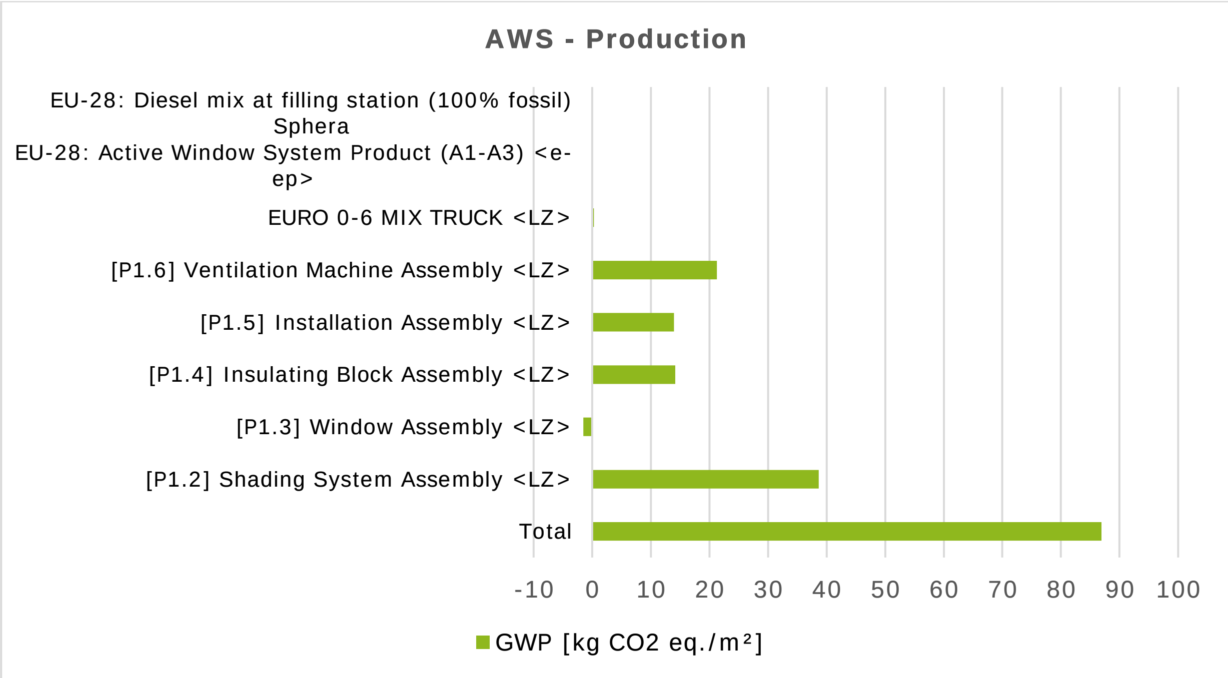

Figure 26: AWS and Sub-assemblies. LCA results. Production phase, GWP100y [kg CO2eq./m²].

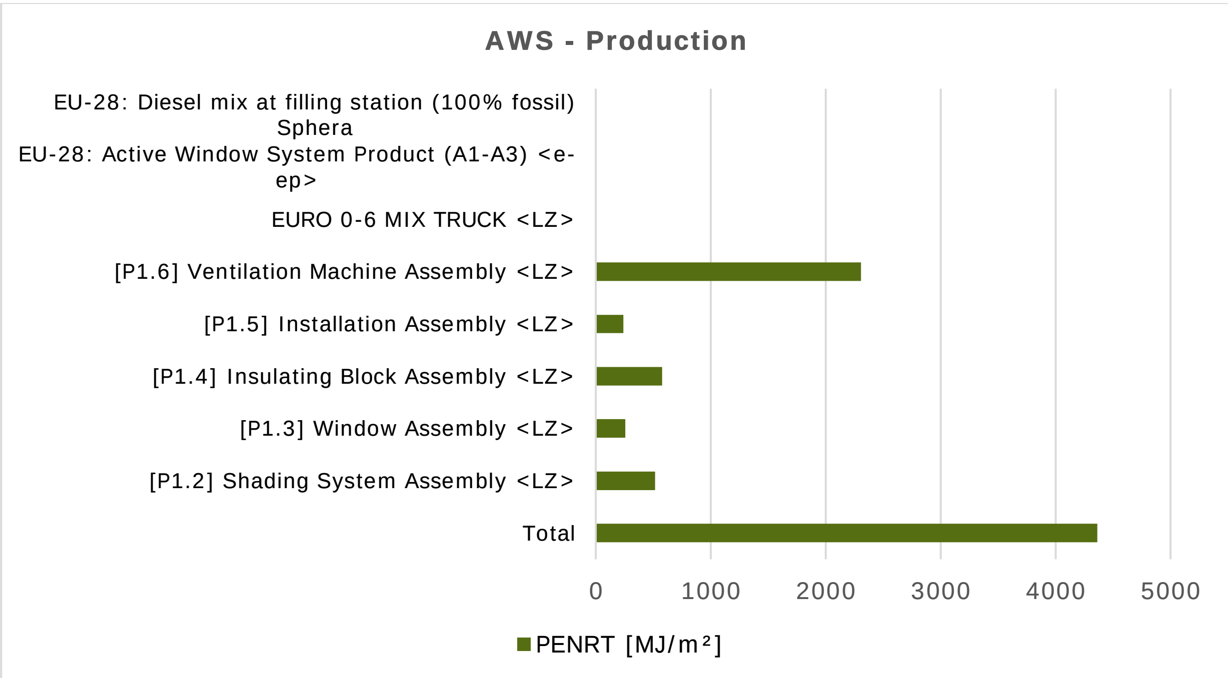

Figure 27: AWS and Sub-assemblies. LCA results. Production phase, PENRT [MJ/m²].

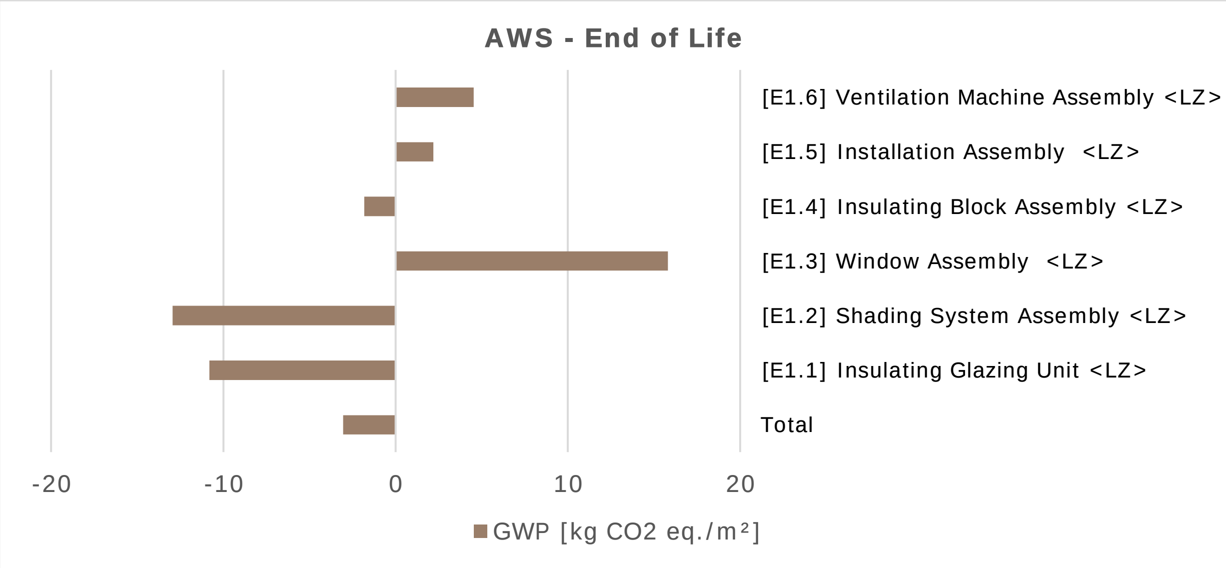

Figure 28: AWS and Sub-assemblies. LCA results. End-of-Life, GWP100y [kg CO2eq./m²].

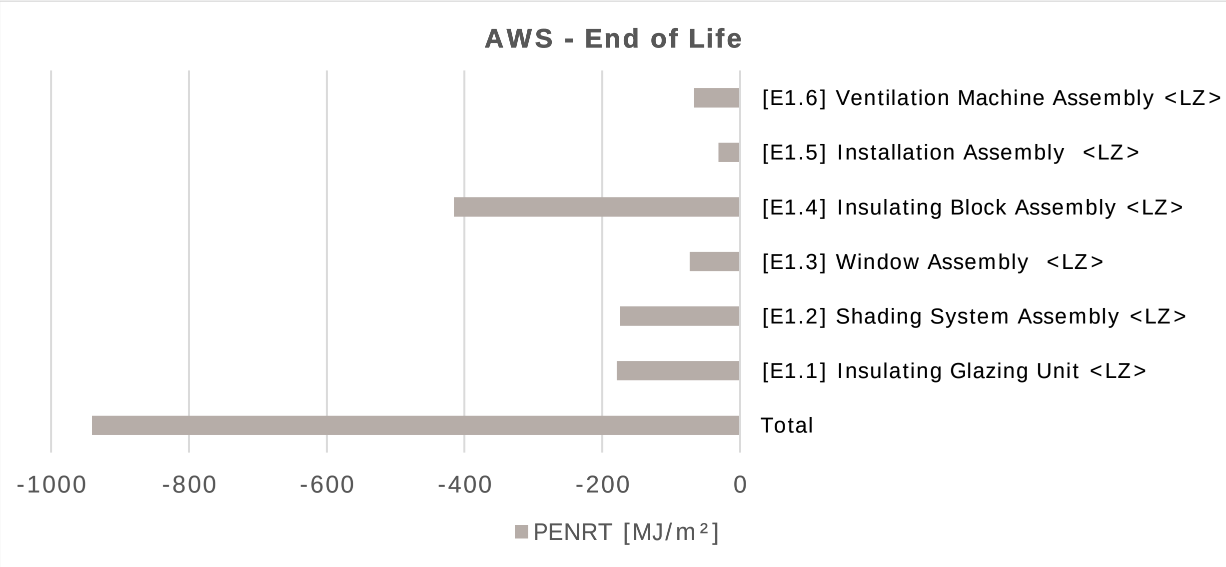

Figure 29: AWS and Sub-assemblies. LCA results. End-of-Life, PENRT [MJ/m²].

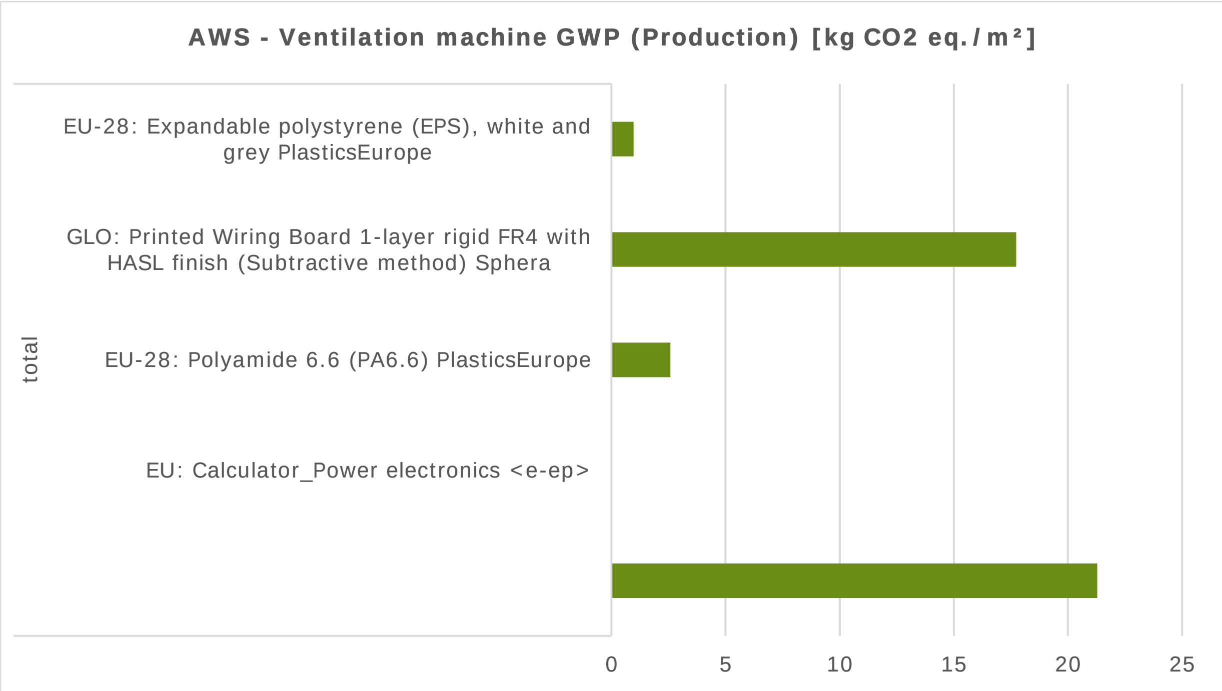

Figure 30: AWS – Ventilation Machine. LCA results. GWP100y [kg CO2eq./m²].

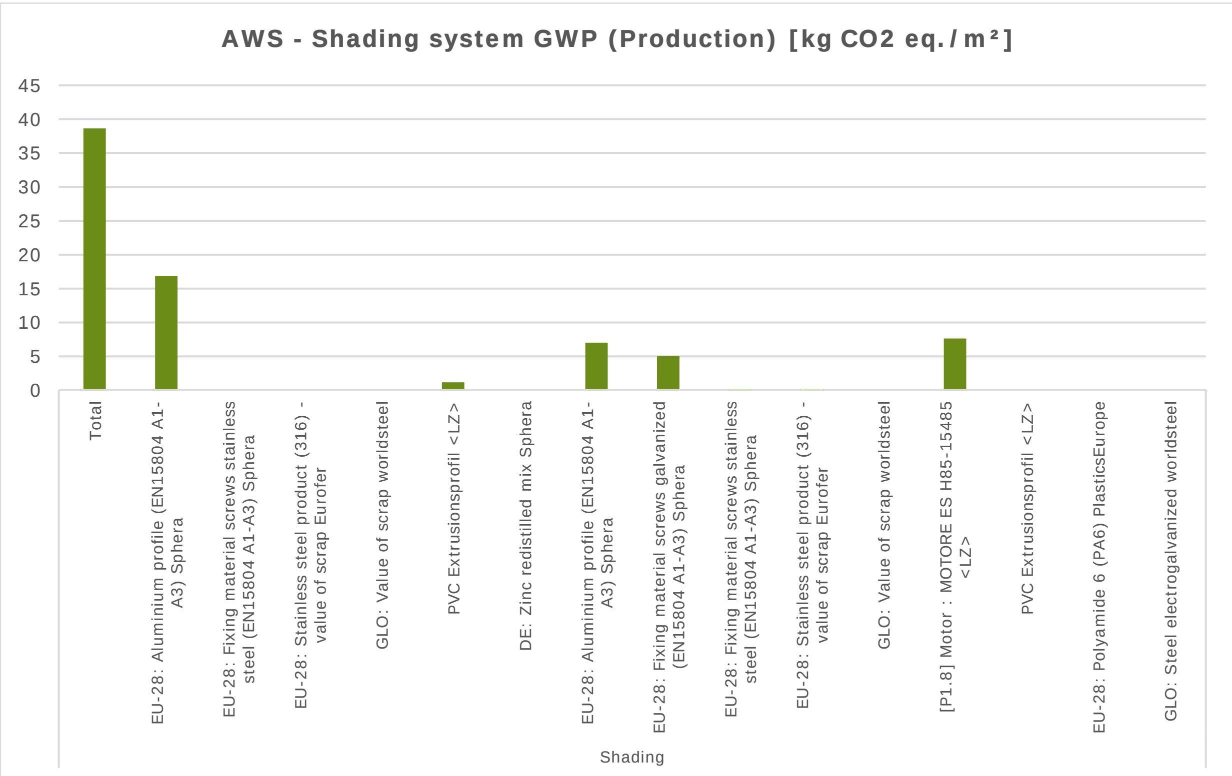

Figure 31: AWS – Shading system. LCA results. GWP100y [kg CO2eq./m²].

5.2 NORDIC® ECO smart air movement technology

NORDIC® ECO is a series of reversible ceiling fans designed from Vortice for residential and commercial applications. It uses an electronically commutated (EC) motor, ensuring higher energy efficiency in comparison to traditional products equipped with alternating current (AC) motors and allowing fine speed adjustment. The advantages of this technology compared to similar technologies, include: no energy spent for cooling, no inclusion of complex components or coolants, minimal maintenance, possibility of installation on ceilings and/or roof beams set at steep angles, electronic control gear of modular design, allowing the addition of further connectivity and control modules, as well as an easy installation [45]

The NORDIC® ECO 120/48"unit technical data are listed below (Table 12):

Table 12: Technical data of the NORDIC® ECO 120/48"unit [45]

Technical Parameters	Technical performance
Maximum fan air flow - **F**	275 m³/min
Fan power input - **P**	30 W
Service value -**SV**	7,833 (m³/min)W
Standby power consumption - **PSB**	0,38 kW
Fan sound power level - **LWA**	52,1 dB(A)
Maximum air velocity - **C**	2,41 m/sec

The geometrical dimensions of the NORDIC® ECO 120/48"unit, are given in Figure 32 and Table 13:

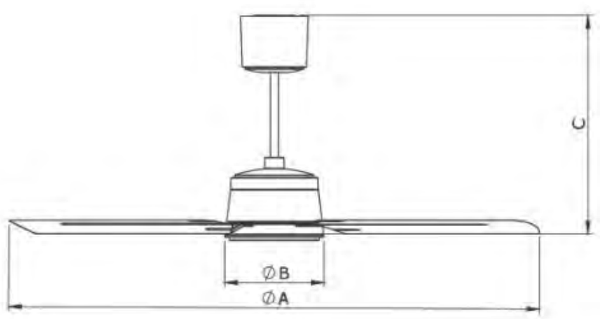

Figure 32: Cross section of NORDIC® ECO 120/48"unit.

Table 13: Dimensions of the NORDIC® ECO 120/48“unit [45].

Geometrical element	Dimension (mm)
A	1218
B	237
C	535

5.2.1 LCA Specifications

Table 14: LCA specification of NORDIC® ECO.

NORDIC® ECO 120/48“ LCA specifications (based on ISO 14044)	
Goal	Environmental profile for the ceiling fan developed from Vortice. The results will be disclosed to public while LCI is confidential. Product specific comparative assertions are not intended within the assessment.
FU (functional unit)	1 item of technology (1 item of NORDIC® ECO 120/48“ ceiling fan)
RSL	20 years
System boundary	Cradle-to-grave system boundary - the product stage (modules A1-A3), - EoL stage (modules C1-C4) - benefits and loads beyond the system boundary (module D)
Cut-off criteria	All data regarding elementary input and output flows of the product system, which are responsible for a minimum of 99 % of the resulting environmental impacts, shall be included in the system. In terms of mass, 95 % of the total mass shall be included in the system (PCR part A and PCR-Part B).
Environmental database	GaBi ts version 10 of the software, using the professional extended GaBi database SP40 [27].
Impact categories	- Global Warming Potential - GWP in kg. CO2 eq. - Total use of renewable primary energy resources - PERT in MJ - Total use of non-renewable primary energy resources - PENRT in MJ
Data requirements	- Characteristics of components: origin, material composition - Geometry: surface in m², material thickness in mm, material mass in kg, etc. - Estimate of the influence on the annual energy demand in the utilisation phase in kWh/a.
Assumptions	Assumption considered for the EoL stage (C + D module): - C2 (transport from building/demolition site to waste treatment/recycling facility), is estimated based on information from the manufacturer. Default scenarios for C2 should be based on representative data, e.g.: national statistics - Plastic, rubber → C3 - municipal incineration with energy recovery; C4 - landfilling of ashes from incineration

	- Metal→C3 - central sorting of mixed construction waste. Recycling of metals; C4 - landfilling of wasted product in sanitary landfill - Mineral wool →C3 - central sorting of mixed construction waste; C4 - landfilling of wasted product in sanitary landfill - Electronics→ C3 - waste of Electrical and Electronic Equipment (WEE) recycling. Incineration of non-recycled parts; C4 - landfilling of ashes from incineration and residuals from recycling/ sorting.

5.2.2 LCA results

Comprehensive results from the LCIA are attached in Annex II.B. Ceiling Fan technology. Here below results for the indicator GWP and PENRT are presented and discussed.

With regard to the NORDIC ECO smart ventilator environmental profile, it can be noticed that most of its potentials lies in the electronics systems, in which is included also the Control Unit with Wi-Fi systems (Figure 33 Figure 34 Figure 35 Figure 36). Especially electronics systems can be, as in this instance, relevant for a product environmental performance. In fact, copper is mostly used and its production can be energy and carbon intensive. Electronics and control device are also packed in plastic elements, which also contributes to the total impact. Alternatives to such materials are at the moment hardly available. Therefore, the role of electronics and control unit in the total PEBs' environmental performance should be better investigated (HMS included).

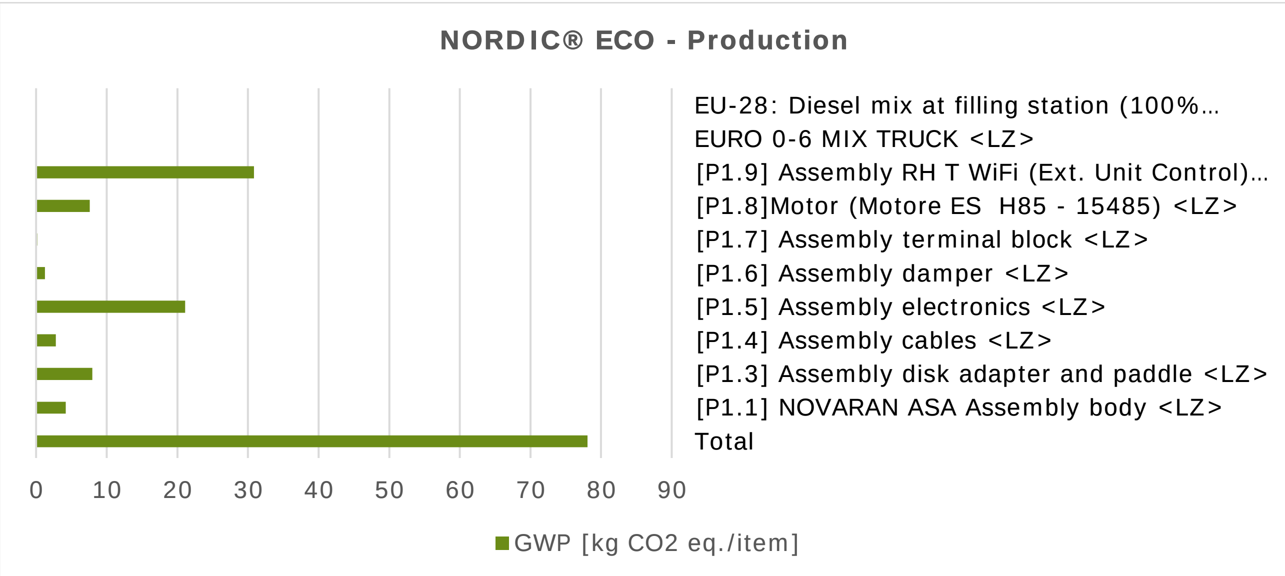

Figure 33: Nordic ® Eco- LCA Results. Production phase. GWP100y [kg CO2eq./m²].

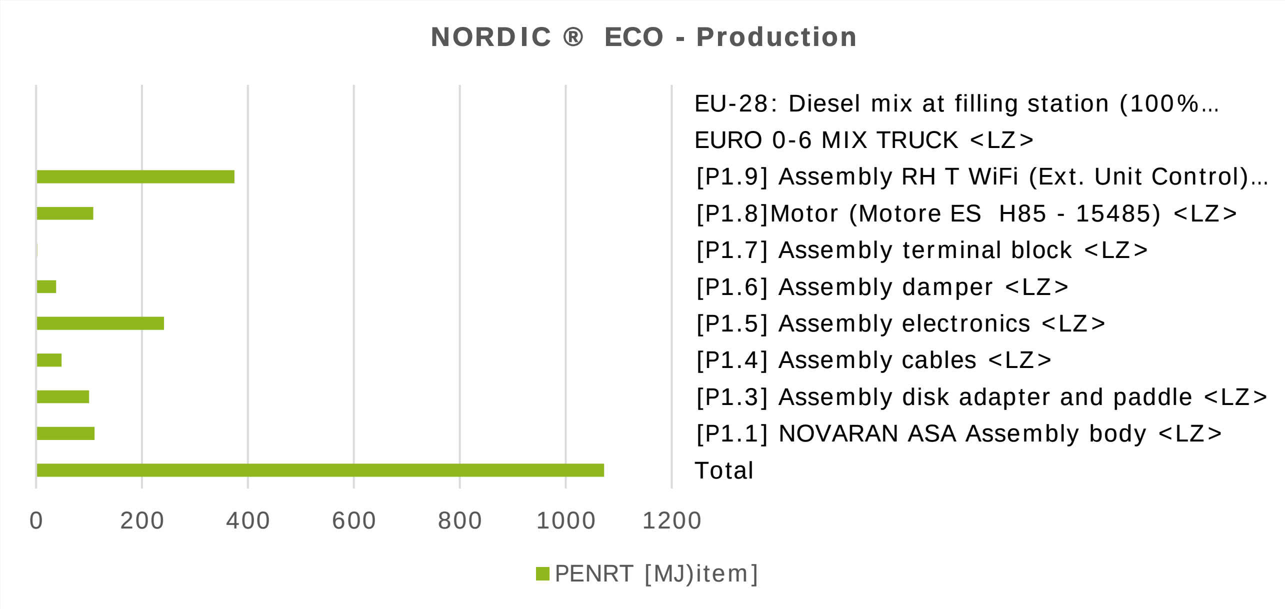

Figure 34: Nordic ® Eco- LCA Results. Production phase. PENRT [MJ/m²].

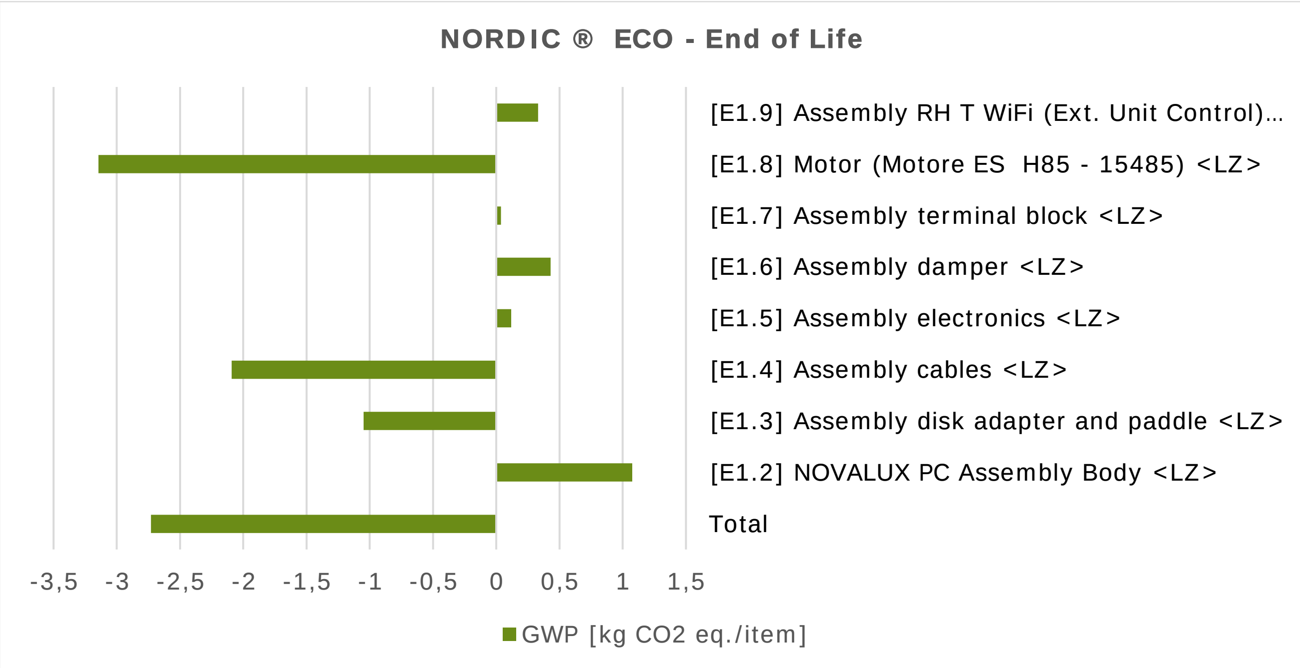

Figure 35: Nordic ® Eco- LCA Results. End-of-Life. GWP100y [kg CO2eq./m²].

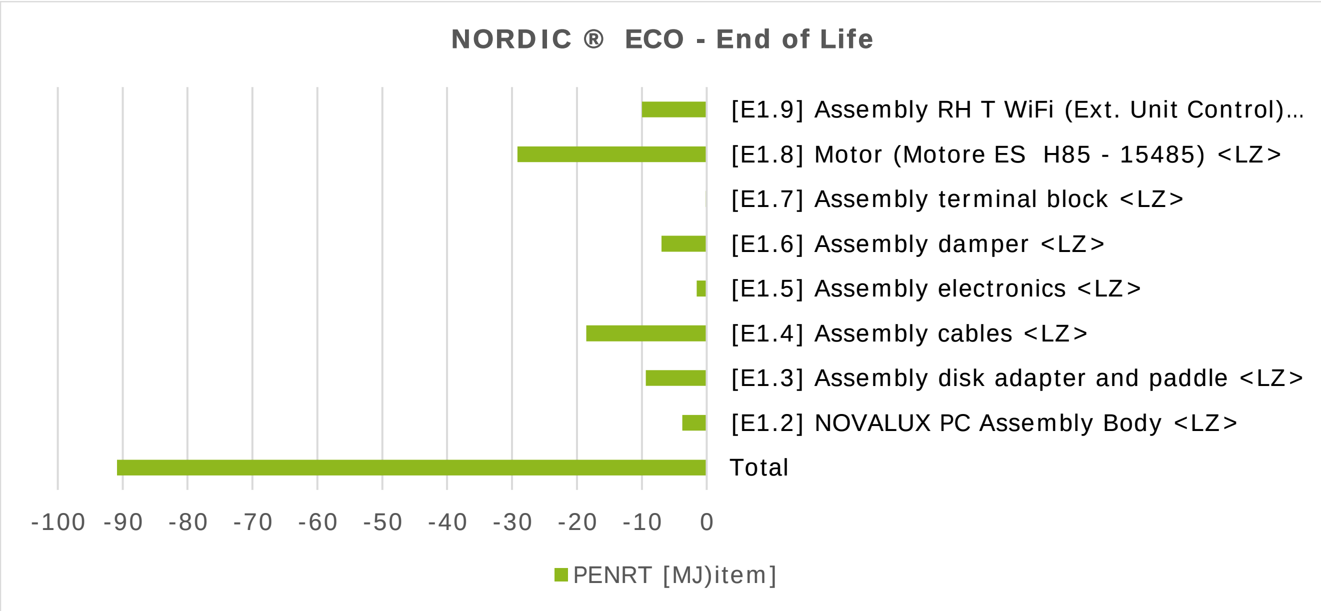

Figure 36: Nordic ® Eco- LCA Results. End-of-Life. PENRT [MJ/m²].

5.3 Ventive Packed Heat Pump (PHP) system

Figure 37: Front and profile view of the Ventive home system (with hybrid storage)

VENTIVE-Home is a fully integrated ventilation, heating and hot water system, which combines passive ventilation with heat recovery (PVHR™) by transferring the thermal energy from exhaust-air to fresh incoming air using heat pump technologies. The integrated technologies in a home environment provides ventilation, hot water and comfort using exhaust air as a source of energy through the combination with a high efficiency heat pump and smart connected controls, enabling in this way adaptability of performance for specific residential requirements (Figure 37). The VENTIVE-Home box includes three technological components:

- *an external-facing cowl* which catches the outdoor air and pushes it into the system,
- *a heat exchanger* where the temperature of the incoming and outgoing air flows is changed in a series of intertwining metallic tubes, relevant to the indoor comfort requirements, and
- *an air flow diffuser* which separates incoming and outgoing air flows.

The Packed Heat Pump system contributes to the accomplishment of Objective 3, allowing management control on the performance of the module through an advanced control management system.

5.3.1 LCA specifications

Table 15: LCA Specification of Ventive PHP system.

Packed heat pump system	
LCA specifications (based on ISO 14044)	
Goal	The lifecycle assessment of the technology aimed to evaluate environmental profile and optimization possibilities. Results are addressed to the project partners to whom the results are of interest for their further project activities, e.g.: to technology developers, demo-case coordinators and relevant parties. Product specific comparative assertions are not intended within the assessment.
FU (functional unit)	1 item[2]
RSL	20 years [46]
System boundary	Cradle-to-grave system boundary based on EN 15804 2020. - the product stage (modules A1-A3), - EoL stage (modules C1-C4) - benefits and loads beyond the system boundary (module D)
Environmental database	GaBi ts version 10 of the software, using the professional extended GaBi database SP40 [27].
Cut-off criteria	All data regarding elementary input and output flows of the product system, which are responsible for a minimum of 99 % of the resulting environmental impacts, shall be included in the system. In terms of mass, 95 % of the total mass shall be included in the system (PCR part A[46]).
Impact categories	- Global Warming Potential - GWP in kg. CO2 eq. - Total use of renewable primary energy resources - PERT in MJ - Total use of non-renewable primary energy resources - PENRT in MJ
Data requirements	- Characteristics of components: origin, material composition - Geometry: surface in m², material thickness in mm, material mass in kg, etc. - Estimate of the influence on the annual energy demand in the utilization phase in kWh/a.
Assumptions	Assumptions for the EoL stage (C + D module): Metals →C3 - central sorting of mixed construction waste. Recycling of metals; crediting for primary material use will be taken into account in D module

[2] The PCR - 4.11 for electricity, steam and hot water generation and distribution (2020) [46] states that the functional unit of a heat pump shall be defined as 1 kWh net of electricity generated and distributed to the customer and/or 1 kWh of steam or hot water generated and thereafter distributed to the customer. Data have been provided from project partner per volume unit (m³). For simplification purposes (comparative assessments are not provided), the functional unit is here however defined as 1 item of packed heat pump technology.

	Wood → C3 - municipal incineration with energy recovery and crediting for electricity and heat production Plastic → C3 - municipal incineration with energy recovery; C4 - landfilling of ashes from incineration

5.3.2 LCA results

Comprehensive results from the LCIA are attached in Annex II.C. Packed heat pump system. Here below results for the indicator GWP and PENRT are presented and discussed. The overall PHP is a complex system, which entails 6 sub-components and each of them can present parts made by more than one material.

With regard to the PHP environmental profile and its sub-components, it can be noticed that most of its potentials lies in the structure, air handler and refrigeration (Figure 38 Figure 39, Figure 40 and Figure 41).

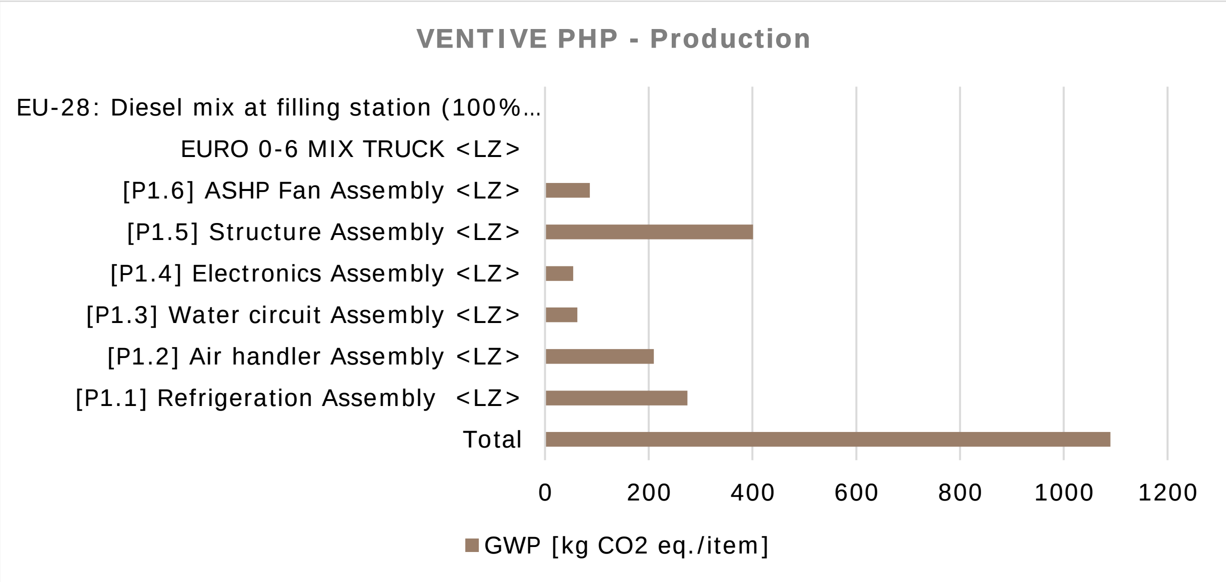

Figure 38: Ventive PHP and sub-assemblies. LCA results. Production phase, GWP100 [kg CO2 eq./item].

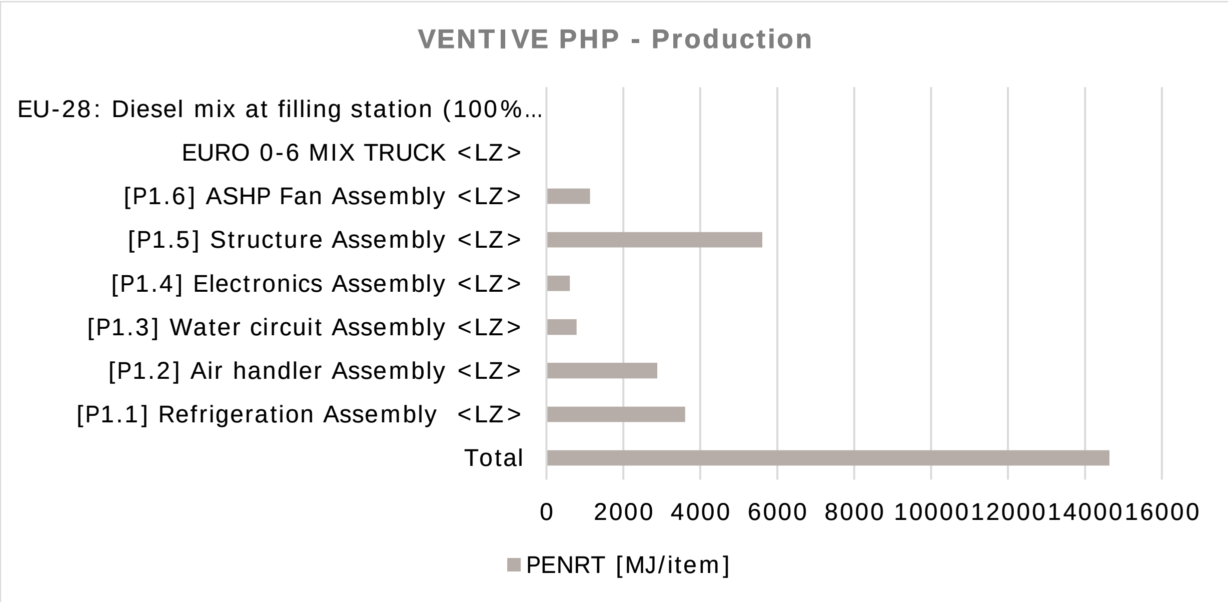

Figure 39: Ventive PHP and sub-assemblies. LCA results. Production phase, PENRT [MJ/item]

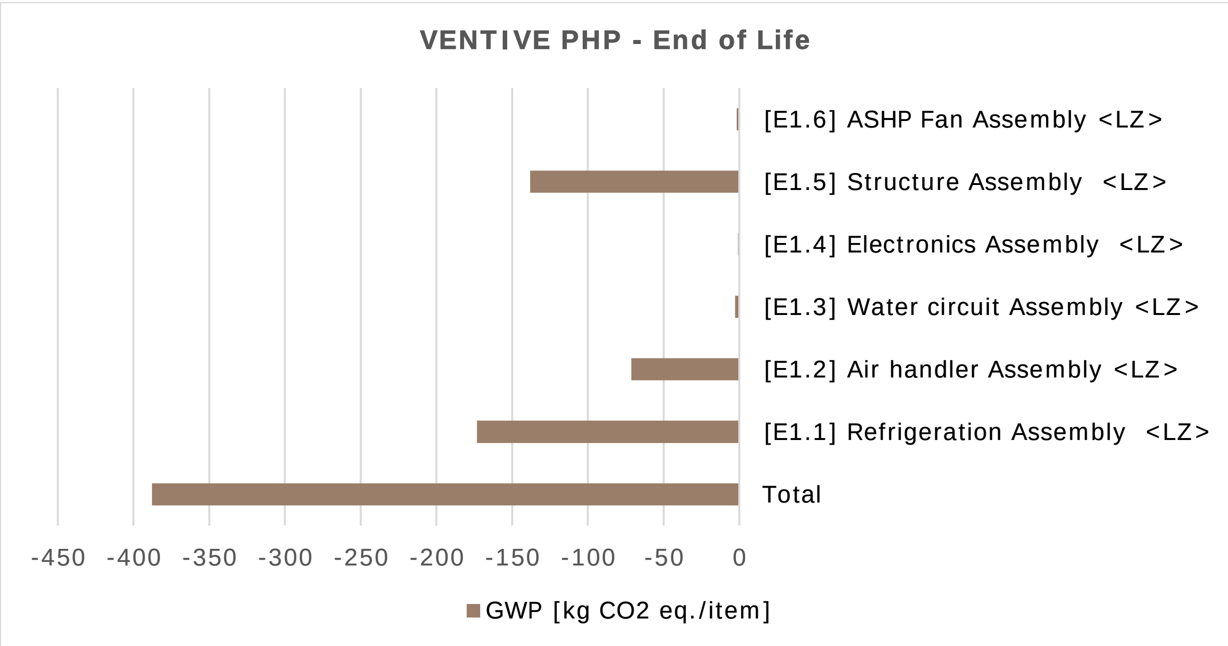

Figure 40: Ventive PHP and sub-assemblies. LCA results. End-of-Life, GWP100 [kg CO2 eq./item]

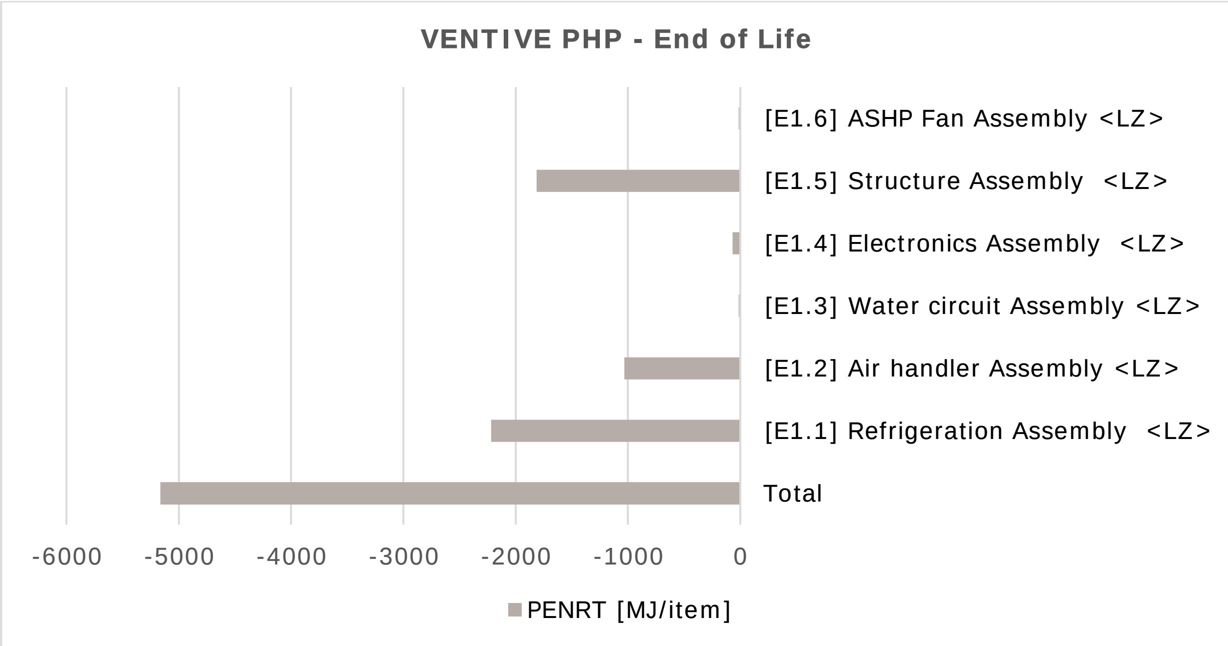

Figure 41: Ventive PHP and sub-assemblies. LCA results. End-of-Life, PENRT [MJ/item]

Focusing on the structure (Figure 42), such sub-component is metallic, made by steel and aluminum, which has an energy and carbon intensive manufacturing. The recycling potential of such materials is not able to compensate the emissions emitted during the manufacturing process.

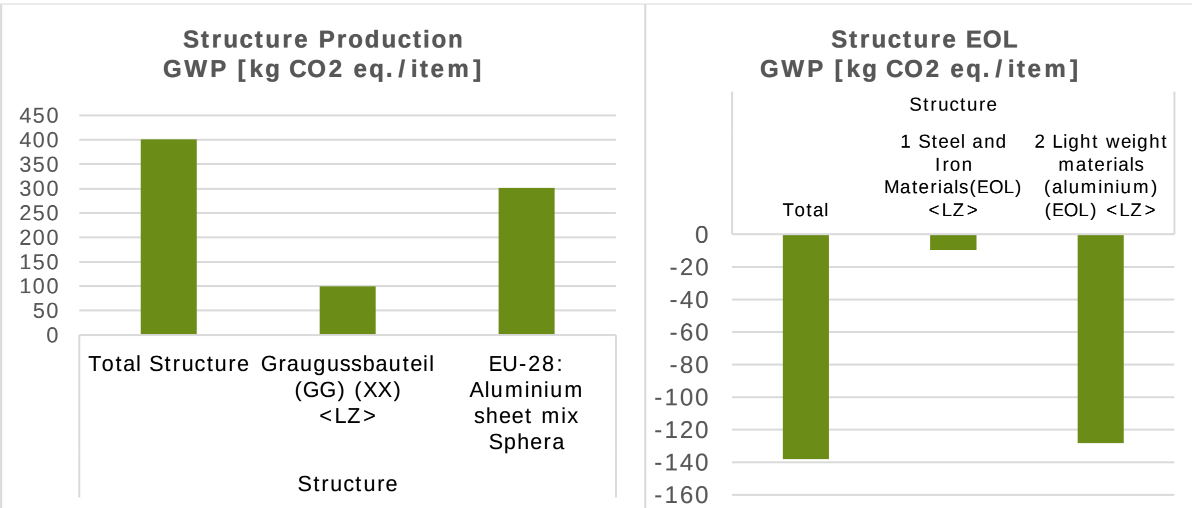

Figure 42 Ventive PHP Structure sub-assembly LCA results. GWP100 [kg CO2 eq./item]

The refrigerator sub-component is also made by metals (aluminum, stainless steel, copper, Figure 43). The aluminum used for the refrigerator's frame has the highest contribution. Aluminum can be also found in the air handler: in these sub-components is has also the highest environmental potential (Figure 44).

In conclusion, due to the significant amount of metals, technology developers are encouraged to optimize the PHP sizing and, consequently, materials' consumption, in order to improve also the overall product environmental performance.

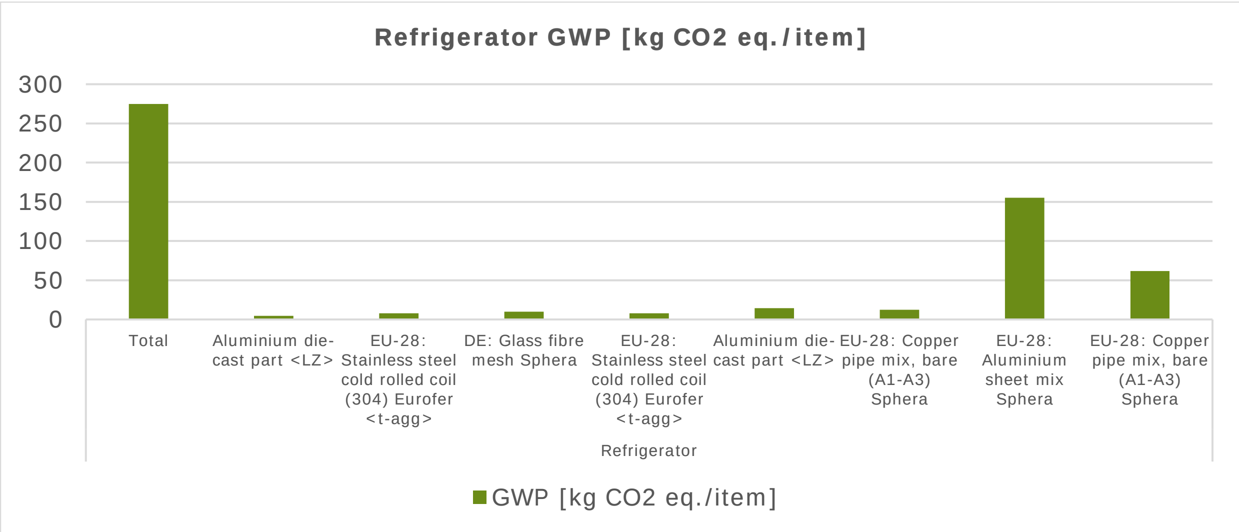

Figure 43: Ventive PHP Refrigerator sub-assembly LCA results. GWP100 [kg CO2 eq./item]

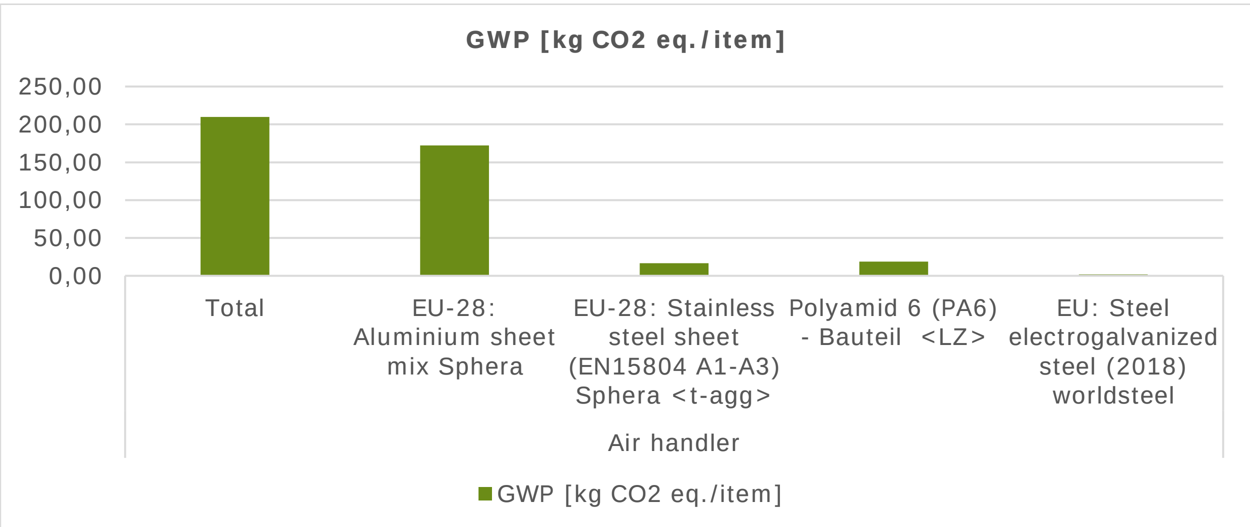

Figure 44: Ventive PHP Air Handler sub-assembly LCA results. GWP100 [kg CO2 eq./item]

5.4 High-capacity hybrid storage (HCHS) – Brunel University

The high-capacity hybrid storage system (HCHS) is developed from the Brunel University and contributes to the creation of the decentralized packed heat pump system. This system combines the thermal energy storage module (TES) using a water tank for the energy storage and the heat pump technology (VENTIVE-Home) using PCM in an advanced control system which interacts with the cloud-based house management system (HMS) from AdvanticSys , for performance control respecting users' requirements (Figure 45).

The objectives of Brunel University are to develop a high-capacity storage module as well as a high-capacity hybrid storage concept. For the accomplishment of these objectives, Brunel University is mainly focused on the testing of Phase Changing Materials (PCM), which will be included in the PHP units provided by Ventive. Testing is carried out for a compact heat store with capacity of 6 kW peak cooling capacity. The Thermal Energy Storage (TES) will be used to store heat for producing hot water and for space heating in buildings. The hot water is heated instantaneously on demand by transferring heat from the PCM to the water flowing through it. The TES can be coupled with air to water heat pumps through plate heat exchangers and copper pipes. In order to charge the PCM an external heat source will be used.

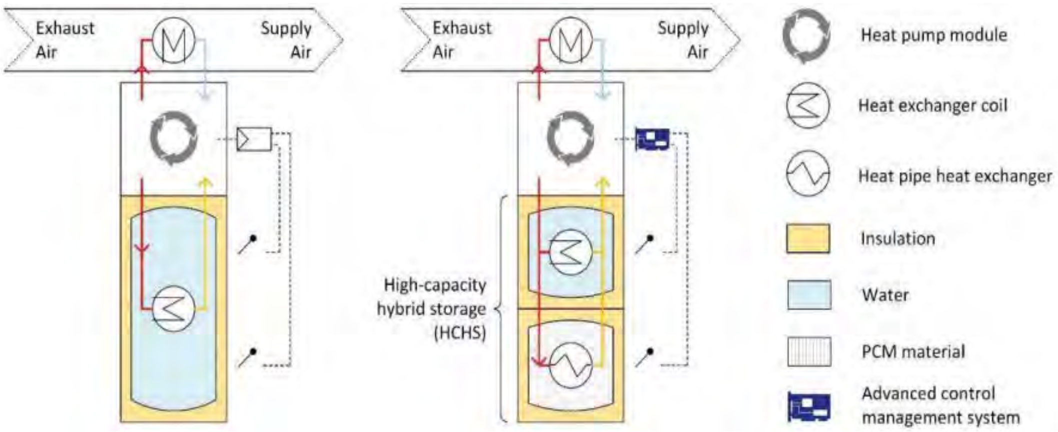

Figure 45: Technical illustration of the decentralized packed heat pump system which integrated the HCHS which combines water and PCM storage and an advanced control system that can interact with the cloud-based HMS

5.4.1 LCA specification

Table 16: LCA specification of HCHS.

High-Capacity Hybrid Storage (HCHS)	
LCA specifications (based on ISO 14044)	
Technology function	Thermal heat storage module (TES module) – for storing heat for hot water and space heating
Goal	Environmental profile assessment. Evaluation of PCR material contribution on the total embodied impacts in comparison with water storage. The results will be disclosed to public, while LCI is confidential. Product specific comparative assertions are not intended within the assessment.
FU (functional unit)	1 kg of combined technical components - 1 kg of thermal heat storage (based on ÖKOBAUDAT generic similar products) [39]
RSL (reference service life)	20 years
System boundary	Cradle-to-grave system boundary based on EN 15804 2020. - the product stage (modules A1-A3), - EoL stage (modules C1-C4) - benefits and loads beyond the system boundary (module D)
Environmental database	GaBi ts version 10 of the software, using the professional extended GaBi database SP40 [27].
Cut-off criteria	All data regarding elementary input and output flows of the product system, which are responsible for a minimum of 99 % of the resulting environmental impacts, shall be included in the system. In terms of mass, 95 % of the total mass shall be included in the system (PCR part A).
Impact categories	- Global Warming Potential - GWP in kg. CO2 eq. - Total use of renewable primary energy resources - PERT in MJ - Total use of non-renewable primary energy resources - PENRT in MJ
Data requirements	- Characteristics of components: origin, material composition - Geometry: surface in m², material thickness in mm, material mass in kg, etc. - Estimate of the influence on the annual energy demand in the utilization phase in kWh/a.
Assumptions	Basic assumption for the EoL stage (C + D module): Metals -> C3 - central sorting of mixed construction waste. Recycling of metals; crediting for primary material use will be taken into account in D module Wood -> C3 - municipal incineration with energy recovery and crediting for electricity and heat production Plastic -> C3 - municipal incineration with energy recovery; C4 - landfilling of ashes from incineration

5.4.2 LCA results

Comprehensive results from the LCIA are attached in Annex II.D. High capacity hybrid storage. Here below results for the indicator GWP and PENRT are presented and discussed. The overall HCHS is a complex system, which entails seven sub-components and each of them can present parts made by more than one material.

With regard to its sub-components, it can be noticed that most of its potentials lies in the TES module and copper pipes (Figure 46 Figure 47), which however can compensate only partially the manufacturing impacts, through good recycling potentials (Figure 48 Figure 49).

Furthermore, assuming water as storage material in the TES Module, which has negligible GWP, the highest GWP contribution is due to the storage containment (made by aluminum, Figure 50) and the its insulation. Other options have been investigated, which entail also Phase Change Materials (PCR) as storage materials. Among the possibilities, Sodium acetate 3-Water seemed a good option, due to its low impact (<1 kg CO2 eq.*kg).

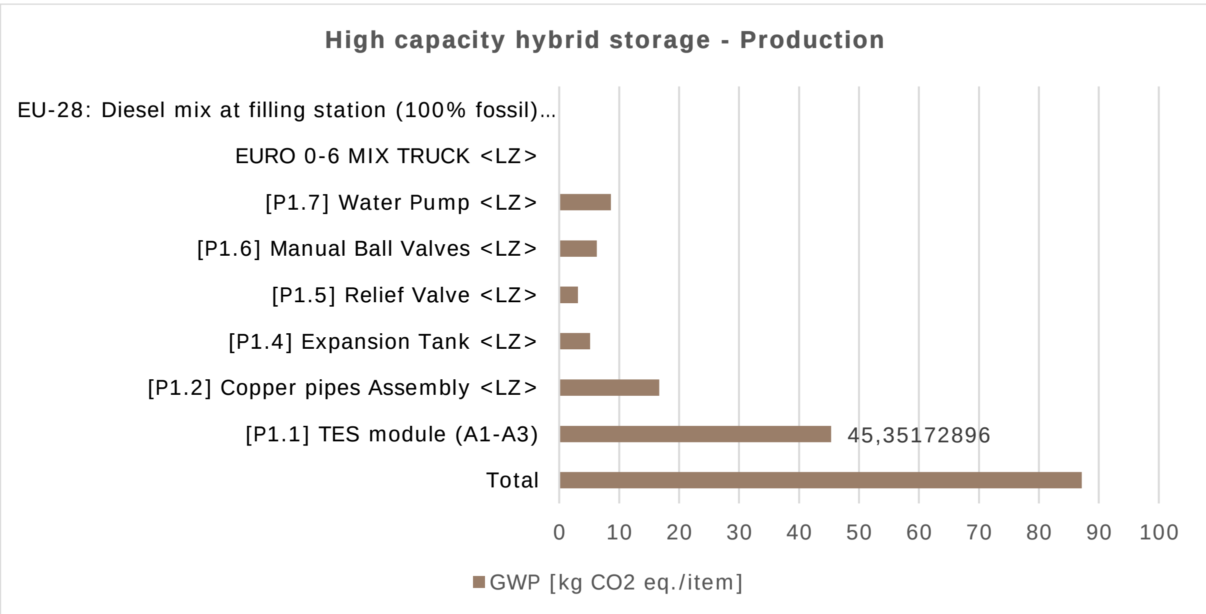

Figure 46: HCHS sub-assemblies. LCA results. Production phase. GWP100 [kg CO2 eq./item]

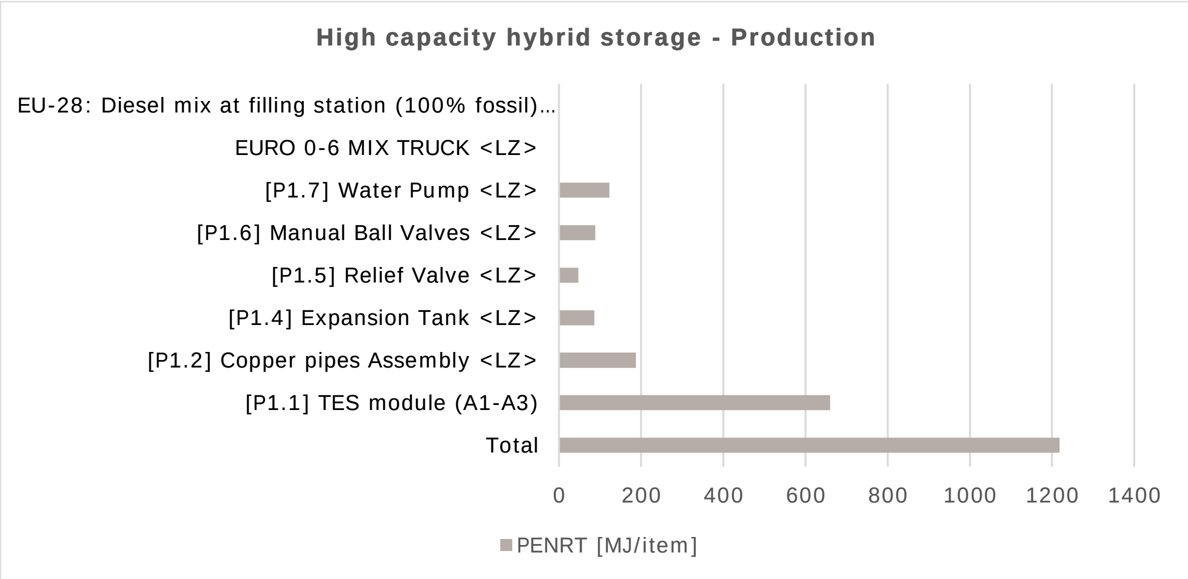

Figure 47: HCHS sub-assemblies. LCA results. Production phase. PENRT [MJ./item]

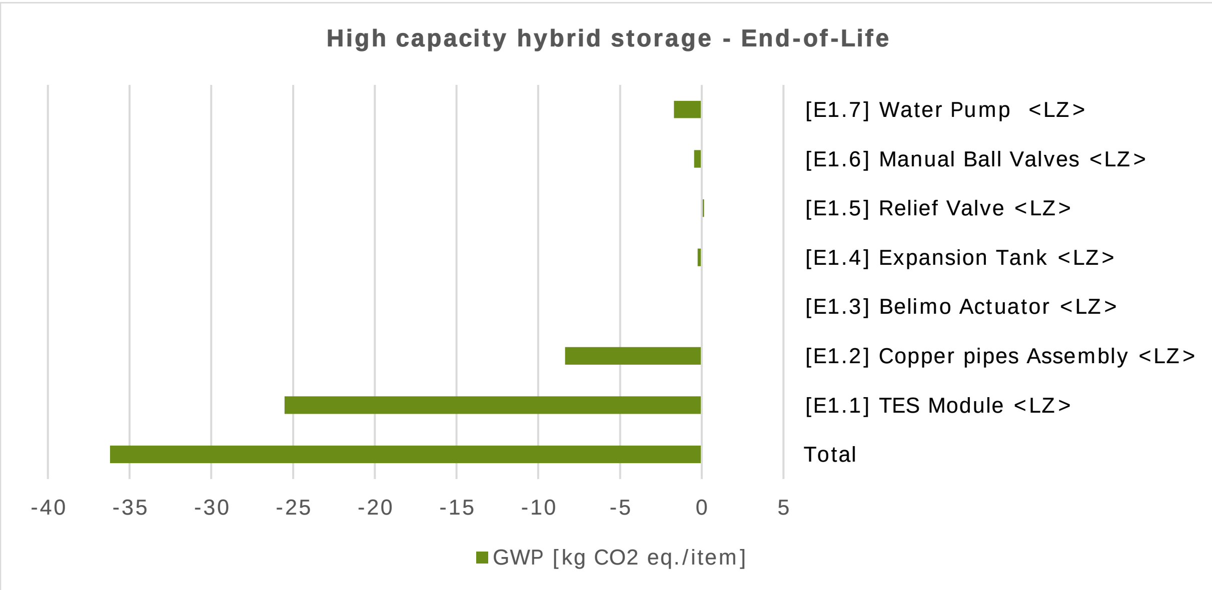

Figure 48: HCHS sub-assemblies. LCA results. End-of-Life. GWP100 [kg CO2 eq./item]

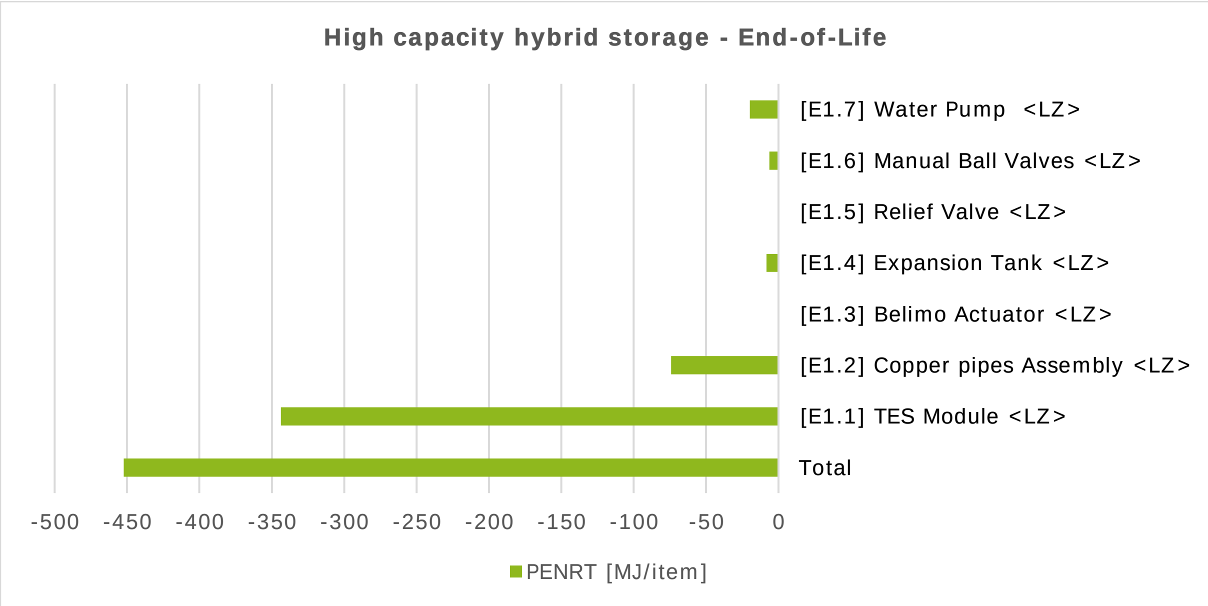

Figure 49: HCHS sub-assemblies. LCA results. End-of-Life. PENRT [MJ./item]

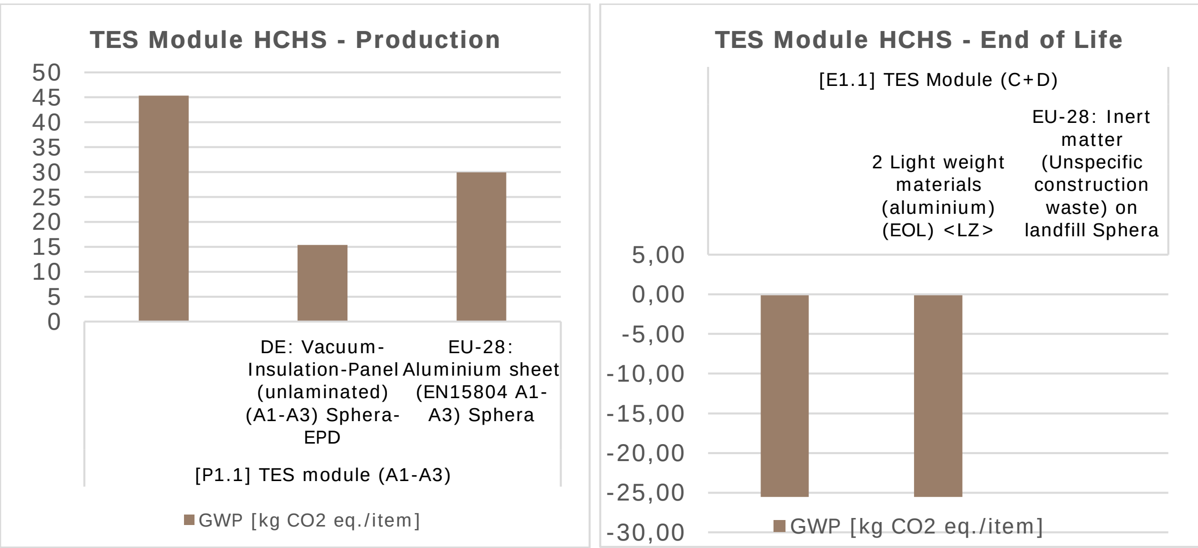

Figure 50: HCHS TES Module sub-assembly. LCA results. GWP100 [kg CO2 eq./item]

5.5 Exemplary lifecycle assessment of PEB's solutions sets.

In this section, an exemplary LCA analysis for PEB's solutions set is reported.

5.5.1 Goal and scope

For this analysis, an exemplary solution set (SS) has been conceived and located in a low-rise (LR) and high-rise (HR) building and four climate contexts. Totally, eight cases have been considered and are here presented. As suggested and established in LCA guidelines for solution sets, the functional system under investigation has been divided in the following building installations components (see also 4.2 for their abbreviations):

- Power Generator for domestic hot water (DHW), space heating (SH) and cooling (SC) - PWG
- Thermal energy storage - TES
- SH/SC Distribution - DISTR
- Ventilation system – VEN
- Pipework, Valves, Circ. Pumps, Heat Exchanger - PIP
- Photovoltaics system – PV

Table 17: Solution set description and specification for low-rise (LR) and high rise (HR) buildings.

Component type	Specifications	LR	HR
PWG	Air-Water heat pump - heating, cooling, DHW by fresh water stations	50 kW	150 kW
TES	Water Storage+ Heating/Cooling buffer in stainless steel units – XPS insulation	1000 l + 500 l Buffer	3000 l + 1500 l Buffer
DISTR	Low temperature fan coil, free cooling	950 W	950 W
VEN	Ventilation and air treatment		
PIP	Copper pipes with XPS insulation. Stainless steel elements (Valves, Circulation pumps and Heat exchanger)	ø52cm x 3m ø38mm x 10m ø38mm x 10m	ø52cm x 3m ø38mm x 22m ø38mm x 22m
PV	Average technology with battery, sized to provide a positive balance	240 m² (estimated)	528 m² (estimated)

According the established guidelines and calculation methods, the selected 4 reference - climate contexts are

- *Mediterranean* (Italy – IT),
- *Continental* (Germany – DE),
- *Oceanic* (France– FR)
- and *Subarctic* (Norway– NO).

Low-rise example is a 663 m² 3-floors' building, provided with 7 dwellings, each between 80-110 m² net surface. High-rise example is a 2912 m² 7-floors' building, with 40 dwellings, each one between 55-80 m² net surface.

For the considered systems, the LCA has been specified according to the Cultural-E guidelines for LCA of PEBs. The chosen functional unit is /m² NFA*year. This in order to understand the share of the provided installation over the whole building system. The analyzed impact category is Global Warming Potential (GWP) 100 years (IPCC GWP100a) - kg CO2 eq.), while other environmental indicators will be provided in other extensive works. The considered lifespan duration is limited to 30 years, which can cover the average service life for building installations. Here in Table 18, LCA specifications are summarized.

Table 18. LCA specification for the Cultural-E solution sets.

LCA specifications (based on [9,10])	
Object	Functional system: solution sets aimed for PEBs
FU (functional unit)	1 m²*y
Lifespan duration	30 years
System boundary	- product stage (modules A1-A3), - Energy operation (module B6) - EoL stage (modules C3-C4) and benefits (module D)[13]
Impact categories	Global Warming Potential 100 years (IPCC GWP100a) [kg. CO_2 eq.][11]
Environmental database	Ökobau.dat[39] , Environmental Product Declaration (EPDs)

The modelling has been carried out through the GENERIS® tool [41] of Fraunhofer Institute for Building Physics (IBP), by using generic environmental databases for construction sector [39] as well as product-specific datasets. For the assessment of the building operation, information on national electricity mix and CO_2 conversion factors have been collected from EU Scenario 2020 [42]

5.5.2 Lifecycle inventory (LCI)

According to designers' specifications, for each building type the following total components where collected (Table 19). This information serves as basis for the calculation of the embodied impacts (lifecycle modules: raw material extraction and production A1-A3; waste C3-C4; credits due to recycling D according to [13]).

Operational energy (B6 module[13]) is derived through building energy simulations on the 4 climate contexts. The total energy demand considered DHW, SH and SC. Results are summarized in for LR Table 20 and Table 21 for HR building.

Table 19. Lifecycle inventory of solution sets for low rise (LR) and high rise (HR) buildings.

Component	LR		HR	
		Total		Total
PWG [unit]		1		1
TES [unit]		1		1
VEN [unit]	3 units* apartment	21	3 units* apartment	60
DISTR [items]	38 IT, 39 DE, 36 FR, 44 NO		121 IT, 115 DE, 137 FR, 103 NO	
PIP	1300 kg cupper 0,2 m³ XPS		3000 kg cupper 0,5 m³ XPS	
PV [m²]		240		528

Table 20. Energy simulation results for LR buildings.

LOW RISE	Mediterranean (IT)	Continental (DE)	Oceanic (FR)	Subarctic (NO)
Qth_user	36.9	33.3	35.3	85.5
Qel _HP	14.1	14.4	13.3	17.7
Qth_HP	47.8	41.1	46.3	48.1
Qel_APL	29.7	31.3	39.6	34.8
Qel_LGT	0.9	0.7	1.2	1.1
Qel_VEN	3.7	3.7	3.7	3.7
Qel_CF	1.1	0.7	1.3	0.8
Qel_aux	0.4	0.5	0.4	1.1
Qel_FNC	2	2.2	2.3	3.3
Total energy demand	+52	+53.6	+61.8	+62.5
PV surface (m²)	172.5	177.6	204.9	207.0
PV credits	-72.35	-72.42	-72.38	-72.45
Energy balance	-20.4	-18.8	-10.6	-10.0

Table 21. Energy simulation results for HR buildings.

HIGH RISE	Mediterranean (IT)	Continental (DE)	Oceanic (FR)	Subarctic (NO)
Qth_user	28.9	27.1	34.4	31.9
Qel _HP	9.8	10.3	10.3	12.8
Qth_HP	36.2	31.7	44.1	37.3
Qel_APL	23.6	26.9	35.6	30.6
Qel_LGT	1.1	0.8	1.9	1.4
Qel_VEN	2.4	2.4	2.4	2.4
Qel_CF	1.6	1.1	1.7	1
Qel_aux	2.4	1.8	8.3	3
Qel_FNC	1.4	1.3	2.5	2
Energy demand	+42.2	+44.6	+62.7	+53.1
PV surface (m²)	614.14	649.43	913.48	772.84
PV credits	-36.28	-36.26	-36.24	-36.28
Energy balance	+5.9	+8.3	+26.5	+16.8

According to the solution sets' LCA calculation methods (see chapter 4.2), the useful thermal energy provided to the whole building - end users (DHW + SH + SC) has been calculated (Qth_user), by considering all thermal losses. Qth_HP is the thermal energy generated by the heat pump (DHW + SH + SC). Furthermore, energy usage consumption (Qel) of the single component has been derived. This includes appliances (APL), lighting (LGT), ventilation (VEN), ceiling fans (CF), auxiliary energy (aux) and fan coils (FNC). The user behaviour has been implemented in the different profiles for occupancy, plug loads and lightning usage. The climatic context has been while considered by using different climatic data, and different building envelopes. The derivation of the total energy demand allowed a first preliminary sizing of PV modules in terms of power (kWp) and surface (m²). With respect to this, 1000 kWh/year for 1 kWp installed (0.2 kWp/m²) were considered as a conservative assumption.

When the calculated total energy balance is negative, as for LR buildings, the functional system produces more energy than its own demand. These are systems aimed therefore for PEBs.

The energy production occurs through PV modules installed exclusively on the roof. When the energy balance is positive, as for HR buildings, there is criticality due a limited roof surface for PV modules. Not surprisingly, the climate area dictates the annual solar yield and the consequently reached PV credits. Another interesting outcome is related to the installations' usage, which seems to be higher in Subarctic example. This cultural aspect might be further investigated and proven with up-to-date data.

5.5.3 Lifecycle impact assessment (LCIA) and environmental payback

Here in Table 22, results of the lifecycle impact assessment (LCIA) are shown. Impacts are specified for each installation component and determined for each building type.

Table 22. LCIA: Solution sets embodied impacts (A1-A3; C;D modules [13]) in LR and HR buildings.

Component	LR GWP [kg CO_2 eq.]	HR GWP [kg CO_2 eq.]
VEN	970.0	3233
PWG	1417.3	3543
TES	282.2	546.8
PV	54528	163584
Tot. embodied [impact/m²]	111.8	57.36
Tot. embodied [impact/m²*y]	3.762	1.948

Lastly,

Table 23 shows operational impacts for each building type and climate context, by taking into the account national electricity mixes and their respective impacts [42].

Table 23. LCIA: Operational impacts of LR and HR buildings in the different cultural-climate context.

National Electricity mix [kg CO_2 eq./kWh]	**Mediterranean (IT)**		**Continental (DE)**		**Oceanic (FR)**		**Subarctic (NO)**	
	0.285		0.337		0.057		0.027	
Tot. B6 [kgCO_2 eq./m²*y]	LR	HR	LR	HR	LR	HR	LR	HR
	-5.80	1.69	-6.34	2.81	-0.60	1.51	-0.31	0.52

As shown in the LCIA results, constructive aspects and therefore embodied impacts can significantly influence the overall lifecycle impact, and photovoltaic modules are main contributor. By accounting embodied impacts only, HR buildings perform a better environmental profile. This is due to an optimized installation of components and larger net floor area for a given building footprint.

Operational impacts related to energy demand only are higher in continental/subarctic climate areas and low-rise buildings. High-rise buildings present in this respect also an optimized thermal energy and electricity consumption. However, due to a higher number of potential users and a more limited roof surface, they should use other surfaces, aiming at a positive energy balance.

As already discussed in this document, in one hand, PV modules are expected to contribute mostly to the total assessed embodied impact. Their environmental performance in PEB's solutions sets can be therefore questionable. On the other hand, they are source of renewable energy during the whole functional system lifespan. In terms of environmental impacts and GHG emissions, they allow credits by avoiding emissions related to energy consumption coming from non-renewable sources.

As a further step, the environmental payback periods (PB) has been derived for each of the considered 8 case studies. PB periods have been calculated by assuming a variable electricity mix, according to the EU Scenario 2020 [42].

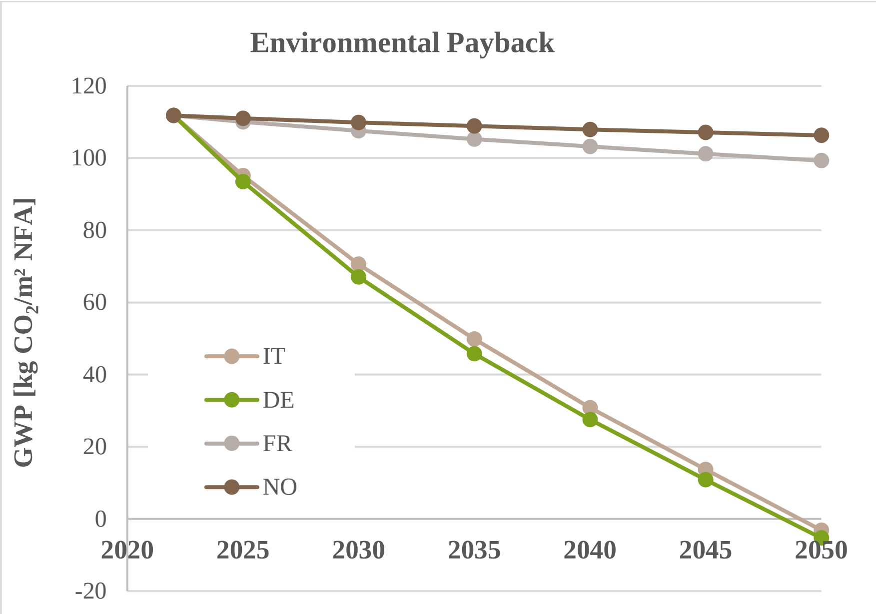

Figure 51: PB periods of the 4 LR Buildings case studies.

As shown here in Figure 51, Italian and German examples reach environmental payback periods by 2050. In the French and Norwegian cases, the payback curve presents a slower trend, which may lead to question the proposed solutions and their environmental advantages. However, France has a nuclear baseline, while in Subarctic region, there are less chances for the installation of local PV, and the energy mix has to change together with a switch of power generation plants types.

With respect to the PB curves' trend, assuming, e.g., French energy mix in the Mediterranean case may lead to very different results. Assuming the Italian energy mix in Continental area may lead while to similar outcomes. In conclusion, PB periods are primarily affected by the national carbon intensities of electricity generation.

5.6 LCA Results discussions

In the previous section, LCA results of PEBs' technologies and solutions set have been presented.

5.6.1 Product level

On the product level, most of the developed technologies may present higher impacts in comparison with traditional technologies. This is especially due to two main root causes.

1) The use of materials with higher environmental impacts. Technologies strongly rely on, metals (aluminium, copper and steel) and plastic.

2) A higher quantity of sub-assemblies requested.

With regard on the first point, the AWS environmental profile was strongly affected by the chosen ventilation machine and shading systems. Both sub-assemblies are not belonging to the own developers' production. In this instance, the technology developer has been encouraged to find other similar products, which may represent better alternatives, such as textile-based shading systems.

A similar issue was found in the NORDIC ECO smart air ventilation system, in which the presence of the electronic components necessary for the smart functionalities had a significant contribution on the environmental performance. In this regard, as for the HMS, it is necessary to evaluate on the higher building levels, if the electricity savings over the building operation due to the smart functionalities can compensate the higher impacts.

The PHP and HCHS system presented high environmental impacts, which are due to the complexity of the both systems, as well as their intrinsic novelty. Systems and sizing optimization that developers will further carry out will be relevant for reducing consumption of metals and plastic components especially.

5.6.2 Solution set

LCA analyses carried out on cultural and climate tailored solution sets identified relevant outcomes for the further research activities related to:

1. technologies and design choices
2. cultural-climate context
3. national energy mix.

In the first instance, the LCIA results proved that photovoltaics systems and their technology level are relevant for the achievement of the system's carbon neutrality. PV modules have in fact the highest share of embodied emissions on the solution set level. Moreover, design choices, and, more specifically, the designed building type may dictate also the operational energy: within high-rise buildings, other surfaces besides roofs need to be spotted aiming at a positive energy balance.

A second issue, which may also represent a barrier for positive operational energy balances, is represented by the climate-cultural area. Due to their temperatures and lower annual solar yields, solution sets located in Continental and Subarctic area can reach, in fact, less energy credits. Moreover, in comparison with, e.g., Mediterranean area, the user-electricity estimated in Subarctic area presented higher records. This cultural aspect deserves therefore further and more in-depth investigations.

Lastly, national energy generation influence primarily the estimated payback periods. In particular, national carbon intensity of electricity production can determine the effectiveness of PEBs, as valuable solutions to accelerate the shift to renewable energy sources by 2050. In the conducted study, a higher effectiveness of the investigated solution sets is found in the Italian and German contexts. For these contexts and such, the implementation of PEBs should be especially encouraged in a very short term and the energy mix can be improved after adding local PV to make each building rewarding by itself. Where, on the contrary, the national energy grid presents already a low carbon intensity, strategies aimed to decrease the initial climate investment should be detected. This may reduce the environmental payback period, by allowing the exploitation of the carbon positivity and increasing stakeholders' willingness to PEBs.

In the overall, the issues identified within the conducted analyses need to be re-considered and re-evaluated on the whole building level. The effective advantages of PEBs' solutions should also be pondered with the inclusion of other aspects (e.g. costs). The derivation of environmental and economic values on exemplary climate and cultural-based PEBs will provide feedbacks to designers' choices and, lastly, make available benchmarks on PEBs. In this regard, the activities of other tasks, and, among them, Task 6.3 of Cultural-E, will be relevant for addressing these objectives.

6 Conclusions

As a prior result of such activities conducted in Cultural-E project, this document presents guidelines on how to understand and carry out LCA analyses on PEBs.

Following defined Cultural-E's KPI evaluation framework for PEBs and a specific literature research on LCA for high-performance buildings, a need for environmental impact assessment of Plus-Energy Buildings on several layers has been recognized. In this regard, the already available needed to be specified, adapted and operationalized when targeting PEBs.

As a first step, an assessment of developed technologies occurred: the collected information aimed to understand primarily what happens at component level and what could be improved. This activity led to discussion and recommendations to technologies' providers and for guiding their engineering processes.

Despite the confidentiality of some models, some LCA results are provided to the reader. With regard to this, LCA results of technologies have been collected and here provided for technologies' developers who are challenging issues related to trading-off products' technical and environmental performance. On the product level, the generated environmental values, lead to some discussions regarding the production processes and End-of-Life routes of the developed building products. Processes critical for the product environmental profile have been detected. Optimization possibilities have been identified, e.g., by saving especially plastic and metallic materials consumption.

For assessing the environmental performance of PEBs' technologies on higher level and under consideration of their operational phase, LCA analyses were also carried out, as a second step, on exemplary solution sets. Parametric LCA models for evaluating the solution sets in buildings have been produced, keeping in consideration KPI framework, energy related habits, technological solutions, and looking forward to the analysis on foreseen for demo cases (next to come in the project). The obtained preliminary results suggested that PEBs seemed to be advantageous especially in Mediterranean area. In such contexts, there is a significant potential for yearly energy credits and electricity mix improvements. On the contrary, there are also national and climate contexts, in which electricity mix presents already low carbon intensity, and there are lower chances of solar energy credits coming from PV systems. In such cases, building developers may face some challenges in achieving the established PEBs' requirements. Hence, strategies aimed to decrease the initial climate investment, i.e. the building embodied carbon, should be detected.

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ANNEX I - Description of impact categories

The assessed environmental impact categories are shortly described within Figure 52, The Global Warming Potential (GWP) describes the environmental effect of an increased warming of the troposphere which is caused by anthropogenic greenhouse gases (Figure 52). Such gases derive e.g., from the burning of fossil fuels.

Global Warming Potential (GWP)

Effect:	Increased warming of the troposphere due to anthropogenic greenhouse gases e.g. from the burning of fossil fuels.
Reference Substance:	Carbon Dioxide (CO_2)
Reference Unit:	kg CO_2 Equivalent
Source:	IPCC (Intergovernmental Panel on Climatic Change)

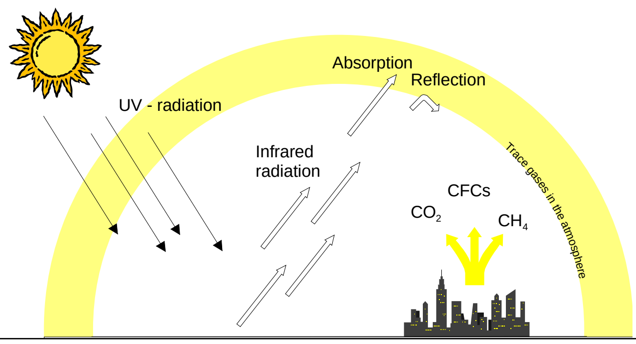

Figure 52 Global Warming Potential (GWP) - environmental relevance (Kreißig. 1999).

Primary energy is the energy content of an energy carrier in his original form. Renewable and fossil primary energy are differentiated. The environmental indicator “primary energy demand” is used as measure for the consumption of primary energy for all life cycle processes or stages connected to the assessed product (e.g., extraction. energy conversion. production and supply processes). Associated environmental impacts are thereby counted back to a necessary amount of primary energy carriers (Table 24).

Table 24 - Environmental indicators - environmental relevance

Environmental indicator	Effect	Reference substance	Reference unit
Non-renewable primary energy demand (PED $_{\text{non-renewable}}$)	Primary energy non-renewable as measure for the consumption of fossil energy carriers (crude oil. natural gas. mineral coal. brown coal. uranium) and therefore as measure for their shortage (based on the approach. that energy carriers are mostly substitutable)	--	MJ

ANNEX II – Summary of LCA results

II.A. Active window system

		GWP [kg CO2 eq./m²]	PERT [MJ/m²]	PENRT [MJ/m²]
	AWS Life Cycle	**274.58**	**1077.00**	**3421.74**
	AWS - End-of-Life stage <LZ>	**-3.05**	**-272.02**	**-940.53**
	[E1.1] Insulating Glazing Unit <LZ>	-10.81	-12.32	-179.02
	[E1.2] Shading System Assembly <LZ>	-7.06	-32.01	-95.09
[E1.2.1] Shading Blinds Assembly <LZ>	1 Steel and Iron Materials(EOL) <LZ>	0.00	0.00	-0.02
	2 Light weight materials (aluminium) (EOL) <LZ>	-7.06	-32.01	-95.07
	1 Steel and Iron Materials(EOL) <LZ>	-0.17	0.16	-1.54
	2 Light weight materials (aluminium) (EOL) <LZ>	-2.93	-13.30	-39.49
	EU-28: Disposal of plastics (landfill/incineration) Sphera <EoL>	0.49	-1.81	-7.93
	DE: Non-ferro metals (others) in waste incineration plant Sphera <t-agg>	0.00	0.01	0.02
	EU-28: Green electricity grid mix (average power plants) (production mix) Sphera	0.00	0.04	0.00
[E1.2.2] Guides and auxilliary components Assembly <LZ>	EU-28: Process steam from natural gas 90% Sphera	0.00	0.00	0.02
	[E1.2.3] Motor Assembly <LZ>	-3.27	-11.31	-30.37
	[E1.3] Window Assembly <LZ>	15.81	-31.15	-73.47
	[E1.4] Insulating Block Assembly <LZ>	-1.83	-149.43	-415.40
	[E1.5] Installation Assembly <LZ>	2.18	-6.69	-31.28
	[E1.6] Ventilation Machine Assembly <LZ>	2.63	-24.58	-121.88
	AWS - Production stage <LZ>	**277.63**	**1349.01**	**4362.27**
	[P1.1] Insulating Glazing Unit <LZ>	31.42	26.86	458.15
	[P1.2] Shading System Assembly <LZ>	38.64	174.22	517.33
	EU-28: Aluminium profile (EN15804 A1-A3) Sphera	16.90	98.00	224.33
	EU-28: Fixing material screws stainless steel (EN15804 A1-A3) Sphera	0.04	0.12	0.54
[P1.2.1] Shading Blinds Assembly <LZ	EU-28: Stainless steel product (316) - value of scrap Eurofer	0.05	0.12	0.59
	GLO: Value of scrap worldsteel	0.00	0.00	0.03
	P1.2.1 Shading blinds Assembly <e-ep>	0.00	0.00	0.00
	PVC Extrusionsprofil <LZ>	1.16	3.75	28.41
	DE: Zinc redistilled mix Sphera	0.10	0.77	1.75
	EU-28: Aluminium profile (EN15804 A1-A3) Sphera	7.02	40.71	93.18
	EU-28: Fixing material screws galvanized (EN15804 A1-A3) Sphera	5.03	8.64	50.74
	EU-28: Fixing material screws stainless steel (EN15804 A1-A3) Sphera	0.22	0.60	2.70
	EU-28: Stainless steel product (316) - value of scrap Eurofer	0.23	0.62	2.95
[P1.2.2] Guides and auxilliary components Assembly <LZ>	GLO: Value of scrap worldsteel	0.02	-0.01	0.14
	[P1.2.3] Motor Assembly <LZ>	7.88	20.89	111.97

	[P1.3] Window Assembly <LZ>	-1.51	293.49	257.68
	[P1.4] Insulating Block Assembly <LZ>	14.18	377.48	578.73
	[P1.5] Installation Assembly <LZ>	13.97	80.78	239.69
	[P1.6] Ventilation Machine Assembly <LZ>	21.29	52.861	503.3
	EU: Calculator_Power electronics <e-ep>	0	0	0
	EU-28: Polyamide 6.6 (PA6.6) PlasticsEurope	2.59	47.71	451.07
	GLO: Printed Wiring Board 1-layer rigid FR4 with HASL finish (Subtractive method) Sphera	17.74	4.75	20.28
		0.97	0.41	31.95
[P1.6.1] Ventilation Machine Electronics <LZ>	EU-28: Expandable polystyrene (EPS), white and grey PlasticsEurope	0.97	0.41	31.95
	[P1.6.2] Ventilation machine insulating box <LZ>			
		0.30	0.00	0.00
EU-28: Diesel mix at filling station (100% fossil) Sphera		0.04	0.02	4.69

II.B. Ceiling Fan technology

	GWP [kg CO2 eq./item]	PERT [MJ/item]	PENRT [MJ/item]
NORDIC ECO 120/48' - Lifecycle	**75.33**	**175.30**	**981.83**
NORDIC ECO 120/48' - End-of-Life stage	**-2.73**	**-30.38**	**-90.87**
[E1.1] NOVARAN ASA Assembly coppa <LZ>	1.56	-6.74	-11.37
[E1.2] NOVALUX PC Assembly Body <LZ>	1.07	-2.19	-3.76
[E1.3] Assembly disk adapter and paddle <LZ>	-1.05	0.94	-9.41
[E1.4] Assembly cables <LZ>	-2.09	-7.18	-18.54
[E1.5] Assembly electronics <LZ>	0.12	-0.28	-1.52
[E1.6] Assembly damper <LZ>	0.43	-1.59	-6.95
[E1.7] Assembly terminal block <LZ>	0.04	-0.10	-0.16
[E1.8] Motor (Motore ES H85 - 15485) <LZ>	-3.15	-10.86	-29.16
[E1.9] Assembly RH T WiFi (Ext. Unit Control) <LZ>	0.33	-2.36	-9.99
NORDIC ECO 120/48" - Production stage	**78.06**	**205.68**	**1072.69**
[P1.1] NOVARAN ASA Assembly body <LZ>	4.19	9.67	110.19
[P1.3] Assembly disk adapter and paddle <LZ	7.98	20.09	99.86
[P1.4] Assembly cables <LZ>	2.81	8.20	47.93
[P1.5] Assembly electronics <LZ	21.11	56.51	241.43
[P1.6] Assembly damper <LZ	1.25	1.16	37.76
[P1.7] Assembly terminal block <LZ>	0.15	0.02	2.43
[P1.8]Motor (Motore ES H85 - 15485) <LZ>	7.61	20.79	108.08
[P1.9] Assembly RH T WiFi (Ext. Unit Control) <EoL>	30.86	83.15	374.58
EURO 0-6 MIX TRUCK <LZ>	0.04	0.00	0.00
EU-28: Diesel mix at filling station (100% fossil) Sphera	0.01	0.00	0.61

II.C. Packed heat pump system

		GWP [kg CO2 eq./item]	PERT [MJ/item]	PENRT [MJ/item]
	Heat Pump - Lifecycle	**701.85**	**3764.**	**9473.**
	Heat Pump - End-of-Life stage <LZ>	**-387.82**	**-1685.**	**-5165**
	[E1.1] Refrigeration Assembly <LZ>	-173.24	-763.51	-2219.67
	[E1.1.1] Air-to-air refrigerant heat <LZ>	-18.32	-83.06	-246.71
	[E1.1.2] Flat plate heat exchanger <LZ>	-0.33	0.29	-2.94
	[E1.1.3] Filter dryer <LZ>	3.91	-4.86	-8.50
	[E1.1.4] Refrig. Expansion valve <LZ>	-0.33	0.29	-2.94
	[E1.1.5] Compressor <LZ>	-54.96	-249.18	-740.13
	[E1.1.6] Copper pipes <LZ>	-6.21	-21.33	-55.05
	[E1.1.7] Refrigeration frame <LZ>	-65.96	-299.02	-888.15
	[E1.1.8] Thermal Store <LZ>	-31.04	-106.65	-275.25
	[E1.2] Air handler Assembly <LZ>	-71.30	-340.25	-1032.63
	[E1.3] Water circuit Assembly <LZ>	-2.77	-5.46	-14.10
	[E1.4] Electronics Assembly <LZ>	-0.81	-4.86	-69.11
	[E1.5] Structure Assembly <LZ>	-138.08	-572.61	-1815.13
[E1.5.1] Frame <LZ>	1 Steel and Iron Materials(EOL) <LZ>	-9.83	8.81	-88.17
[E1.5.2] Base, middle and top assemblies <LZ>	2 Light weight materials (aluminium) (EOL)	-128.25	-581.42	-1726.97
	[E1.6] ASHP Fan	-1.64	1.47	-14.69
	Heat Pump - Production <LZ>	**1089.68**	**5449.54**	**14638.66**
	[P1.1] Refrigeration Assembly <LZ>	274.66	1241.35	3601.76
	[P1.1.1] Air-to-air refrigerant heat exchanger <LZ>	4.78	18.63	81.61
	[P1.1.2] Flat plate heat exchanger <LZ>	8.06	24.08	108.48
	[P1.1.3] Filter dryer <LZ>	10.09	19.82	184.13
	[P1.1.4] Refrig. Expansion valve <LZ>	8.06	24.08	108.48
	[P1.1.5] Compressor <LZ>	14.35	55.88	244.84
	[P1.1.6] Copper pipes <LZ>	12.38	33.99	138.81
	[P1.1.7] Refrigeration frame <LZ>	155.02	894.90	2041.33
	[P1.1.8] Thermal Store <LZ>	61.91	169.96	694.07
	[P1.2] Air handler Assembly <LZ> l	209.81	1061.18	2882.04
	[P1.3] Water circuit Assembly <LZ>	62.63	249.66	785.76
	[P1.4] Electronics Assembly <LZ>	54.39	123.94	607.56
	[P1.5] Structure Assembly <LZ>	400.89	2276.15	5611.35
[P1.5.1] Frame <LZ>	Graugussbauteil (GG) (XX) <LZ>	99.46	536.06	1642.10
[P1.5.2] Base, middle and top assemblies <LZ>	EU-28: Aluminium sheet mix Sphera	301.43	1740.09	3969.25
	[P1.6] ASHP Fan Assembly <LZ>	86.12	497.17	1134.07
EU-28: Diesel mix at filling station (100% fossil) Sphera		0.15	0.09	16.12

II.D. High capacity hybrid storage

	GWP [kg CO2 eq./item]	PERT [MJ/item]	PENRT [MJ/item]
Heat Storage - Lifecycle	**50.93**	**248.03**	**765.70**
Heat Storage - End-of-life stage <LZ>	**-36.20**	**-147.95**	**-452.36**
[E1.1] TES Module (C+D)	-25.53	-115.80	-343.80
2 Light weight materials (aluminium) (EOL) <LZ>	-25.56	-115.84	-344.13
EU-28: Inert matter (Unspecific construction waste) on landfill Sphera	0.02	0.04	0.33
[E1.2] Copper pipes <LZ	-8.36	-28.74	-74.17
[E1.3] Belimo Actuator <LZ>	-0.03	0.34	-0.05
[E1.4] Expansion Tank <LZ>	-0.26	-0.44	-8.25
[E1.5] Relief Valve <LZ>	0.14	0.39	-0.08
[E1.6] Manual Ball Valves <LZ>	-0.47	0.19	-6.27
[E1.7] Water Pump <LZ>	-1.69	-3.90	-19.76
Heat Storage - Production	**87.13**	**395.99**	**1218.06**
[P1.1] TES module (A1-A3)	45.35	277.84	660.24
DE: Vacuum-Insulation-Panel (unlaminated) (A1-A3) Sphera-EPD	15.38	104.83	265.58
EU-28: Aluminium sheet (EN15804 A1-A3) Sphera	29.97	173.01	394.66
[P1.2] Copper pipes Assembly <LZ>	16.68	45.78	186.94
[P1.3] Belimo Actuator <LZ>	1.86	6.67	25.98
[P1.4] Expansion Tank <LZ>	5.15	12.70	86.23
[P1.5] Relief Valve <LZ>	3.10	12.19	46.82
[P1.6] Manual Ball Valves <LZ>	0.14	0.27	3.81
[P1.7] Water Pump <LZ>	0.04	0.12	0.90
EURO 0-6 MIX TRUCK <LZ>	0.07	0.00	0.00
EU-28: Diesel mix at filling station (100% fossil) Sphera	0.01	0.01	1.15