Integrated Systems

Integrated environmental and economic assessment

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This work has been carried out by:

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Abbreviations

Table 1 List of abbreviations

BEMS	Building Energy Management Systems
BoM	Bill of Materials
BTES	Borehole Thermal Energy storage
COP	Coefficient of Performance
DTI	Danish Technological Institute
DTU	Technical University of Denmark
FU	Functional Unit
HIG	University of Gävle
LC	Life cycle
LCA	Life cycle analysis
LCE	Life cycle economics
LCI	Life cycle inventory
LCIA	Life cycle inventory analysis
MCE	Magnetocaloric Effect
NCSRD	National Centre For Scientific Research “Demokritos”
PCR	Product Category Rules
PSYCTOTHERM	G. Ligeros & SIA OE - Psyctotherm
PVT	Photovoltaic-Thermal Collector
USTUTT	University of Stuttgart
VCHP	Vapour-Compression heat pump
DB	Database
MCHP	Magnetocaloric heat pump
DS	Dataset
MWT	Main water tank
BWT	Buffer water tank
spcBWT	Space buffer water tank

Executive Summary

This document aims to provide the specifications and results of the Life Cycle Assessment (LCA) and Life Cycle Economics (LCE) of the considered systems in the EU-funded project RES4BUILD (under grant agreement No 814865), within the objectives set in WP6 – *Life cycle analysis and validation of the platform*. The defined framework for the LCA and LCE of the technologies serves the environmental and economic assessment of the technologies in WP2 and of the prototype systems in WP5, and is fed with information from the simulations of the integrated technology systems in WP5 for delivering environmental and economic impact of the operational phase.

The specifications for the environmental and economic assessment of the technologies under consideration and the assessment results of the study are described incrementally as depicted in Figure 1: Document structure

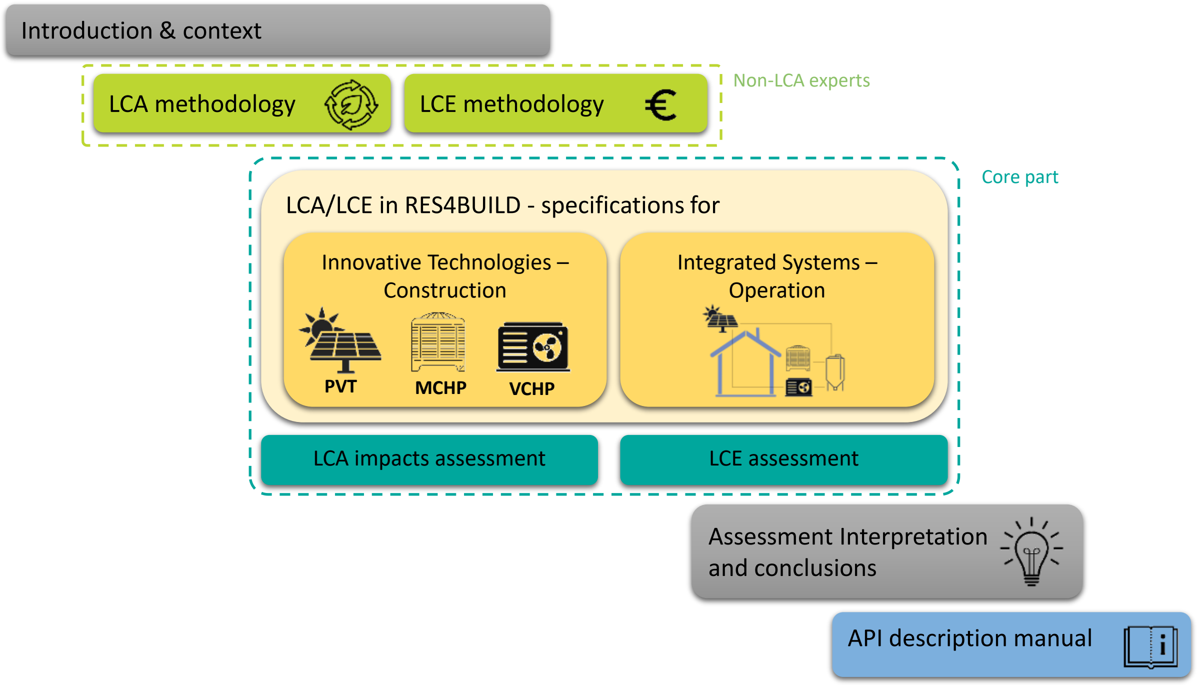


Figure 1: Document structure

In the first chapter –*Introduction and context*, a general description of the study's objectives is presented, the key issues of the report are thematised and the relevance of the environmental and economic assessment in RES4BUILD concludes the chapter. The Life Cycle Assessment (LCA) and Life Cycle Economics (LCE) methodologies are described in the second part of the report, to which references on international norms and standards of the applied methodologies are made. The third part of the report represents also the core contribution of USTUTT to RES4BUILD. This part defines the LCA and LCE specifications for the environmental and economic assessment in two levels, namely the construction aspect of the technologies, and the operational aspect of the combined technologies as integrated systems. Based on ISO 14040 and ISO 14044 norms, the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) follow thereafter. LCE specifications and LCE assessment results are defined in parallel to the LCA specifications and results for both technology levels. Final results of the LCA and LCE for the separate technologies and the integrated systems are complemented by interpretation analysis and main conclusions at the end of the report. The API manual describing the function and application of it for the end-user, concludes the report (confidential).

The LCA and LCE specifications are defined for the photovoltaic-thermal collector (PVT collector) developed from MG Engineering, the magnetocaloric heat pump (MCHP) from Technical University of

Denmark (DTU), and the vapour compression heat pump (VCHP) investigated by LIGEROS, G., & CO. O.E. "PSYCTOTHERM".

The LCA is based on the methodology for environmental assessment as described in ISO 14044 and ISO 14040 standards. Additionally the EN 15804+A1, EN 15643 and EN 15978 are considered. The LCE specifications for the economic assessment are based on the VDI 2884, the ISO 15686-5 standard and DIN EN 16627 norm.

The LCA is conducted using the environmental assessment software GaBi (GaBi Software System and Database for Life Cycle Engineering, Sphera Solutions GmbH, Version 10.5.0.78, Schema 8007) while for the economic assessment mainly statistical data based on EUROSTAT2021 are applied. The results in form of environmental profiles containing environmental impacts and cost information for the whole life cycle of the technologies are then uploaded as specific datasets in GENERIS® software to enable automated data transfer, while making use of the dedicated RES4BUILD-API for environmental and economic information exchange.

The impact assessment results are described in detail for the separate technologies and the integrated systems with respect to global warming potential (GWP in kg. CO_2 eq.), while the results for the rest of the environmental indicators are presented at the end of the report in Annex II. Results of the LCA in terms of GWP and results of the LCE of the technologies are shown in Table 2: GWP results and costs assessed for the considered technologies below:

Table 2: GWP results and costs assessed for the considered technologies

Global Warming Potential (GWP) for technology [kg. CO_2 eq.]				Costs for technology [€]			
	Production	**End of life**	**Life Cycle**	**Before use**	**During use**	**After use**	**Total**
PVT	384,27	-40,71	343,55	134,17	4,03	-18,55	119,64
MCHP	3675,84	-1861,42	1814,42	1535,34	-	-440,39	1094,41
VCHP	403,71	-65,73	337,97	515,47	230,78	-74,81	671,44

LCA and LCE specifications defined and described in this report refer exclusively to the technologies investigated in RES4BUILD. A direct comparison of these technologies to similar conventional technologies falls out of scope of the study, due to inconsistency of boundary conditions in a comparison case with technologies extracted from literature. Such a comparison is therefore not carried out and not recommended. Nevertheless, significant conclusions are drawn out of the LCA and LCE standalone analyses of the technologies in respect to the potential of impacts reduction by material composition, and end-of-life scenarios of components:

- For the PVT collector, the highest GWP impact comes from the solar cells as part of the PVT receiver assembly. The consideration of end-of-life scenarios which can compensate for the high impact coming from their production can lead to GWP emissions reduction.
- For the MCHP, the considerable use of metals other than the magnets (such as: cast iron, aluminium and steel) are the main contributors to GWP. In this sense, the reduction of metals mass (weight) in the overall material composition as well as reuse and recycling of magnets can lead to reduced environmental burden.
- For the VCHP, metals used for heat exchange (steel, copper and bronze) are the main contributors to GWP coming from their production, in consistency with their high material share in the material composition. Considering end-of-life scenarios which compensate for the high impact coming from their production, such as recycling and reuse of these materials can lead to lower environmental impact.

The integrated systems-LCA, analyses the environmental impact during the operational phase of the technologies in a building setting, for a residential and an office building type, considering the energy supply in Greece and Denmark, where the two pilots are implemented. In total there are four case studies analysed. LCA results in terms of GWP and the LCE results for the integrated systems are shown in Table 3: GWP results and costs assessed for the considered integrated systems in the pilots below:

Table 3: GWP results and costs assessed for the considered integrated systems in the pilots

Case study	Global Warming Potential (GWP) for case study [kg. CO_2 eq. * annual]	Costs for operational phase [€ * annual]
GR – RES	1100,115012	296,6
DK – RES	269,8259892	386,92
GR – OFF	583,8737318	157,41
DK – OFF	309,5982679	443,96

RES – Residential
OFF – Office
GR – Greece
DK – Denmark

The LCA and LCE results for the RES4BUILD integrated system in four case studies are compared to the environmental and cost impact results of two conventional solutions (Solution 1: an air-source heat pump; Solution 2: a gas boiler combined with an air-conditioner) in buildings, in order to analyse the benefits of the RES4BUILD integrated system in relation to conventional energy production systems. From this comparison are identified the following environmental and costs reduction potentials:

Table 4: GWP reduction and electricity costs reduction by substituting two conventional technology solutions with the RES4BUILD integrated system

Case study	Solution to be replaced by the RES4BUILD system	GWP reduction	Electricity costs reduction
GR – RES	Solution 1 (air-source HP)	7%	7%
	Solution 2 (gas boiler & AC)	24%	42%
DK – RES	Solution 1 (air-source HP)	40%	40%
	Solution 2 (gas boiler & AC)	51%	64%
GR – OFF	Solution 1 (air-source HP)	16%	16%
	Solution 2 (gas boiler & AC)	69%	24%
DK – OFF	Solution 1 (air-source HP)	13%	13%
	Solution 2 (gas boiler & AC)	68%	22%

Based on the boundary conditions defined in this study, the reduction potentials in GWP and costs achieved by substituting two conventional energy production solutions with the RES4BUILD integrated system, demonstrates that significant improvement in environmental and economic impact can be attained by the RES4BUILD system in buildings, and the implementation of innovative technologies investigated within the project. These results do not take into account energy and cost credits gained for returning energy/ electricity in the grid, in case of surplus quantities produced, a consideration of which would lead as a consequence to higher benefits.

General Introduction and Context

Recent reports attribute 28% of worldwide energy-related GHG emissions to building operations and to heating and/or cooling, hot water supply, ventilation and air conditioning and lighting. Still, the IPCC recalls pathways to lead building GHG emissions to be reduced by 80–90% by 2030 in order to reach a fossil-free and near-zero energy construction sector by 2050. In this context, a reduction of emission focused mainly on energy efficiency is not a sufficient measure. Other environmental emission hotspots have to be recognized and for most of the building types, these are concrete, precast and reinforced elements, which are the most important contributor to embodied energy use (EEU) [1] [2] [3].

Given the above, there are a lot of efforts on both construction sectors and research for fostering novel and improved technologies. Furthermore, methods and calculation tools able to provide cradle-to-grave analyses with a sufficient level of detail and data quality are under investigation.

RES4BUILD aims to contribute to accomplishing the goals:

- Putting energy efficiency first
- Achieving global leadership in renewable energies
- Providing a fair deal for consumers,

presented on 30 November 2016 in the package “Clean Energy for all Europeans” by the European Commission. In this context the main goal in RES4BUILD is to achieve decarbonisation in the energy consumption of buildings, by integrating innovative energy technologies in combined systems in buildings, and optimizing the energy demand through building energy management systems (BEMS).

In RES4BUILD, The University of Stuttgart (USTUTT) has lead role in *WP6 – Life Cycle analysis and validation of the platform*, and is therefore responsible for all activities related to life cycle assessment. Work effort for WP6 is divided in three tasks:

1. Task 6.1 - Environmental-economic technology assessment

   The Life Cycle Assessment (LCA) and Life Cycle Economics (LCE) methodologies are presented as well as specifications for LCA of the innovative technologies investigated in WP2 are defined in Task 6.1. Complete results coming from the LCA of the considered technologies are included in technology fact-sheets (first version), which will be updated and prepared for publication towards the project’s end. Information on databases and references used for the LCE is also included in the first version of fact-sheets. The LCA/LCE framework for RES4BUILD are presented in a confidential report at M6, whereas technology fact-sheets with LCA results are delivered at M30 in written report as *Deliverable 6.1 – Technology fact sheets, including technological, environmental and economic key values.*

2. Task 6.2 - Integrated life cycle modelling and optimization

   This task addresses the work on Life Cycle Assessment (LCA) of combined technologies in integrated system-solutions. The LCA applied under a system context, delivers environmental impact of the operational phase of technologies with no consideration of the building’s structure and relevant influence factors on the building’s energy consumption. Part of Task 6.2 is the delivery of an Extensible Markup Language (XML) format for data structure according to ILCD data format [4], for the implementation of economic indicators coming from the LCE.

   Results of LCA and LCE on the operational stage of the technologies, are presented in this report including detailed LCA and LCE analyses of each technology from Task 6.1 and interpretation of results.

The XML-format is enriched with LCA and LCE indicators and used for the creation of an API for enabling automated (environmental and economic) data transfer dedicated to RES4BUILD technologies. A confidential description manual of the API is delivered internally.

3. Task 6.3 - Validation of the simulation platform

   University of Stuttgart is not leader of Task 6.3, nevertheless it contributes to the accomplishment of the foreseen activities in this task through its expertise in LCA. The validation of the platform is planned to start in the upcoming weeks, and results are expected to be finalized in M48.

The work of USTUTT in this report regards three aspects:

- Life Cycle Assessment (LCA) – analysis of environmental impacts for the production and end-of-life stage of the investigated technological components, assessment of impact for the integrated systems prototypes in the operational phase , and also informing the case-studies on environmental impacts of the RES4BUILD system in order to analyse the possibilities of achieving reduction of emissions of the whole building system.
- Life Cycle Economics (LCE) – analysis of the life cycle costs of the investigated technological components, as well as costs of the integrated systems during the operational phase.
- Application Programming Interface (API) – for the exchange of environmental and cost information defined specifically for the RES4BUILD technologies, through a dedicated Extensive Markup Language (XML) structure.

The LCA and LCE is applied for the investigated technologies in WP2- "Development of the innovative technology components", namely:

- **Photovoltaic-thermal (PVT) collector**, developed from MG Engineering
- **Magnetocaloric heat pump (MCHP)**, developed from the Technical University of Denmark (DTU)
- **Vapour-compression heat pump (VCHP),** developed by PSYCTOTHERM

The EeBGuide guidelines for building products and the recommended standards are used as basis for the assessment [5] [6]. The standard impact categories provided in the EN 15804 norm [7] are covered. The assessment includes all relevant life cycle phases: production phase, end-of-life phase as well as impacts within service life. For the environmental assessment, the LCA methodology as described in EN ISO 14040 [8] and ISO 14044 [9] standards is applied.

The general description of the LCA methodology and specific description of its phases are presented in the following chapters.

The LCE is based on the Life Cycle Costing (LCC) methodology defined in the VDI 2884 [10] guidelines and on the ISO 15686-5 standard [11] and DIN EN 16627 norm [12].

Relevance of Environmental and Economic Assessment in RES4BUILD

In accordance to the main objective of RES4BUILD for achieving CO_2 emissions reduction in the building sector through investigating the performance of technological integrated systems for buildings' energy production, the environmental assessment delivers information throughout the project's progress on environmental impacts of the technology related decisions. Additionally, the economic assessment contributes with information on costs throughout the whole technology life cycle. Both the environmental and the economic assessment in RES4BUILD are applied tools aiming to deliver replicable solutions of integrated technologies for energy production for buildings that match the selection and interaction of technologies to RES4BUILD solutions.

For the achievement of such an objective, the work is carried out as depicted in Figure 2: Workflow for the environmental and economic assessment in RES4BUILD

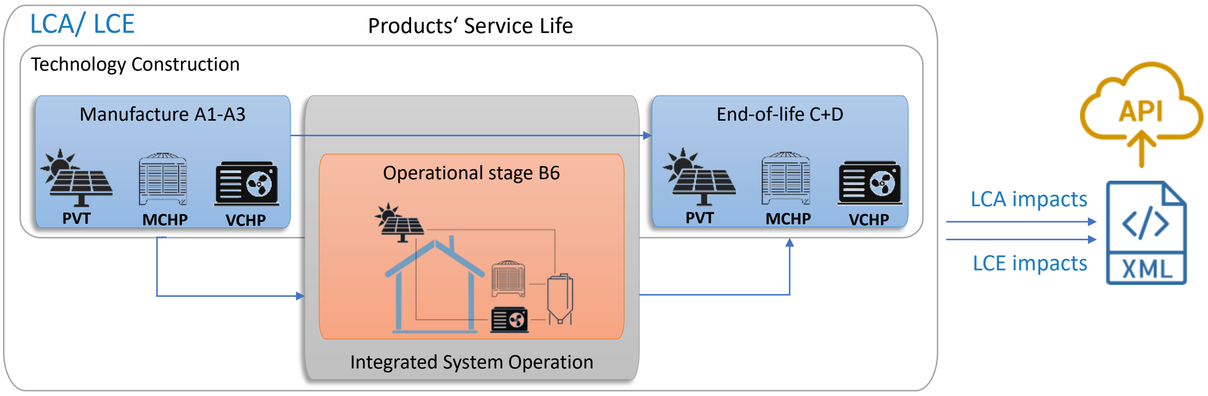


Figure 2: Workflow for the environmental and economic assessment in RES4BUILD

- The required LCA and LCE in RES4BUILD, proceeds in structured tasks: Analysis of the environmental impacts for the production and end-of-life stage of the separate technologies (environmental assessment of the technology construction considers the life cycle phases A1-A3 for the manufacture of the components and the life cycle phases C+D for the treatment of components at the end-of-life)
- Calculation of costs for the production and end-of-life of the separate technologies (costs assessment of the technology construction considers the costs required during the manufacturing of components; life cycle phases A1-A3 and costs charged at the end-of-life of the components; life cycle phases C+D)
- Environmental Impact Assessment (LCIA) of the integrated systems prototypes during the operational phase (environmental assessment during the operational phase considers only impact caused by the energy consumed from the system in a building context)
- Calculation of costs for the integrated systems prototypes during the operational phase (assessment of costs during the operational phase takes into account only the costs coming due to the energy consumed/extracted of the integrated system(s) from the electricity grid)
- Delivery of environmental impacts results and economic assessment results to the relevant consortium collaborates for further research tasks.
- Upload of the environmental and economic assessment results in a dedicated XML structure which is used for the information exchange in the API
- Creation of the API for enabling easy exchange of environmental and economic related information between primary datasets and automatic assessment tools (e.g.: GENERIS®)
- Delivery of a confidential description manual of the API for the end-user within the project

For achieving a holistic analysis, this work delivers results for the whole service life of separate assessed technologies, and one-year impact results for the building operation. The study takes into account energy embodied in the materials and involved in the construction of the technologies, and embodied emissions in energy consumed throughout the operation of the systems, based on a life cycle approach.

The Life Cycle Assessment (LCA) methodology

Description of the life cycle assessment methodology

The Life Cycle Assessment (LCA) methodology is defined as the "compilation of an inventory of relevant energy and material inputs and environmental releases" of products and services for their whole life cycle, from the extraction of resources, to the product manufacturing, until the end-of-life stage (disposal) (Figure 3: Depiction of product life cycle). The Life Cycle Assessment (LCA) study is conducted based on the principles and framework defined in ISO 14040 [8] and the requirements and guidelines defined in ISO 14044 [9].

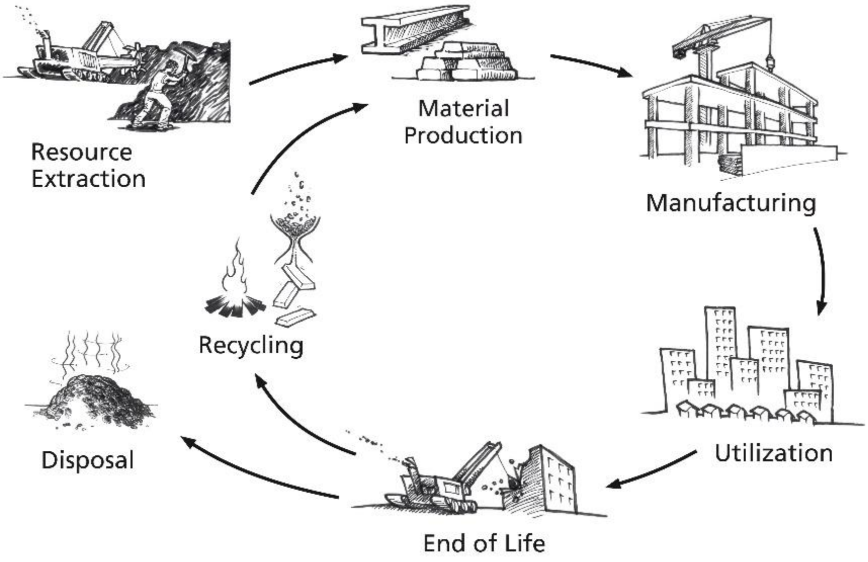


Figure 3: Depiction of product life cycle

The term life cycle depicts a flow-oriented cyclical life of a product. The raw material obtained at the beginning of a product's life cycle as primary product is used to obtain intermediate products, which combine, afterwards with other intermediate products in the manufacturing stage to produce a final product. The latter is then transported to its destined facility marking the start of its use stage. After the use stage, which is temporary, the product is removed from the facility to undergo the end-of-life processes, i.e.: dismantling, recycling, landfill etc. The recycled products can be broken down to their individual components and passed on to pre-production processes, which can result in major savings, since there is no need for the primary product to be dismantled, leading to conservation of resources. If the product on the other hand is no longer usable, it has to be disposed of and has to be recycled (Figure 3: Depiction of product life cycle).

An LCA study includes four phases, which serve a specific purpose in the process of environmental impact assessment (Figure 4: Stages of a Life Cycle Assessment (LCA) [8]) [8].

1. Goal and scope definition phase
2. Inventory analysis phase (Life Cycle Inventory -LCI)
3. Impact assessment phase (Life Cycle Impact Assessment - LCIA)
4. Interpretation phase

In the first phase of the LCA study depending on the intended use, the system boundary and level of detail are defined. In the life cycle inventory (LCI) phase, relevant data on the materials and technologies need to be collected, in order to define correctly the input and output flows of the system. In the life cycle assessment (LCIA) phase the purpose is to provide additional information for the assessment of the product system's LCI results. In this phase the results from the life cycle inventory are multiplied with the characterization factors for each impact category, in order to calculate the values of each environmental impact indicator. In the final phase of the LCA, which is the interpretation phase, the results of the LCIA are summarized, discussed and followed by decision-making strategies in accordance to the goal and scope definition [8] [9].

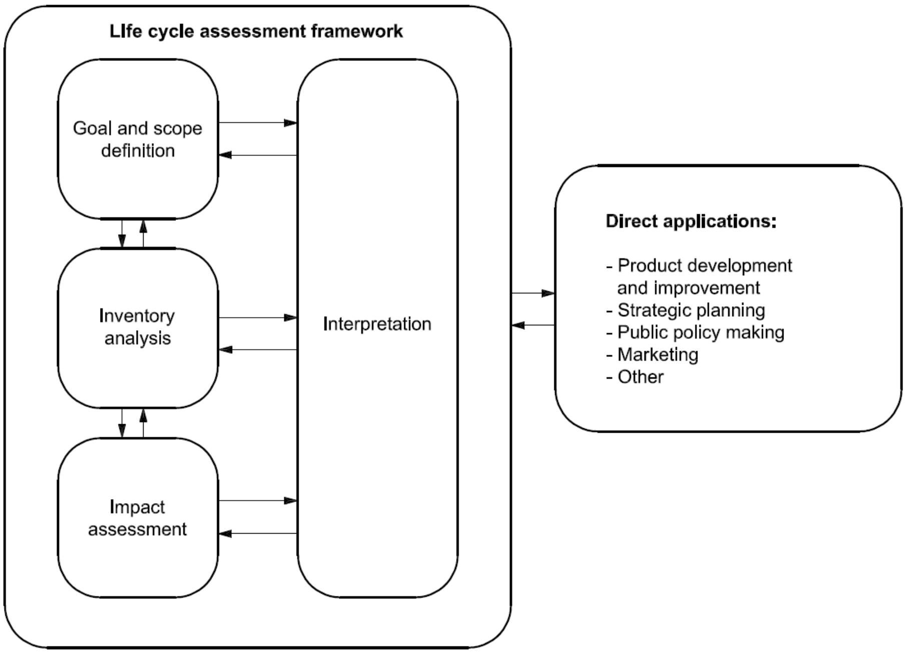


Figure 4: Stages of a Life Cycle Assessment (LCA) [8]

In the construction field, supplementary standards have been established for the assessment of environmental impacts. The EN 15804 [7] standard presents core rules for the product category of construction products and Environmental Products Declaration (EPDs). The EN 15643 [13] Standard has established the sustainability assessment of buildings and civil engineering work, while the EN 15978 [14] presents the calculation method.

For a better understanding, the main definitions and basic knowledge is provided in the following sections.

Goal and scope of the assessment

The definition of the goal and scope is the first step of an LCA, in that it presents an explicit statement of context, and delineates the assessment steps and results communication to the target audience. Structuring the assessment steps for a specific study is carried out through defining the following main points of the goal and scope, in order to ensure consistency with the intended application:

- System boundary
- Functional unit
- Key assumption for the analysis (cut-off criteria)
- Selection of impact categories

System boundary

The system boundary in an LCA study determines which unit processes and which life cycle parts are to be included in the assessment. The definition of system boundary 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. Defining the system boundary is partly based on the scope phase and on subjective choices which can be based on the analysed technological system and nature [7]. 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. The system boundary must consider time horizon as well, since LCAs are carried out to evaluate present impacts and predict future scenarios. Time horizon boundary should be limited consistently with the technologies involved and pollutants' lifespan. On technological systems, interrelations among product systems can be considered as well.

For buildings, the system boundary is established in consideration of its life cycle phases (Figure 5: Life cycle stages in a cradle-to-grave system boundary [7])

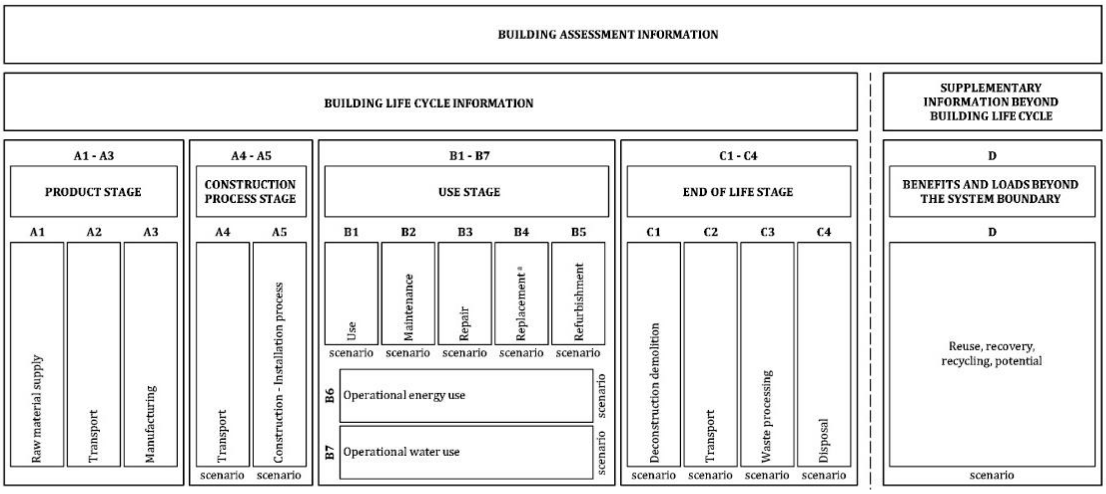


Figure 5: Life cycle stages in a cradle-to-grave system boundary [7]

In the context of building LCA, collected information relevant to the building's environmental assessment can be assigned to different lifecycle phases. The information in Figure 5: Life cycle stages in a cradle-to-grave system boundary [7] covers the product manufacturing (A1-A3), the 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). For the environmental assessment of technological performance, which will be integrated in a building and will eventually function throughout its operational stage, the same life cycle phases need to be considered alongside the building's assessment. In Figure 5: Life cycle stages in a cradle-to-grave system boundary [7] the relevant information available in most building LCA studies is depicted.

Functional unit, declared unit

The functional unit (FU) is defined in ISO 14040 [8] and 14044 [9] as the quantification of the performance of a product system. It is used as the reference unit for the product's LCA study and any comparative assertions. 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 the building sector, the life cycle assessment (LCA) is regulated by EN 15804 [7] and EN 15978 [14], where EN 15804 defines a functional unit (FU) and a declared unit, while EN 15978 defines a functional equivalent.

For buildings, the functional unit is usually defined in *m^2 (net surface dwelling) * y (year)*. It contains the specification of the function (dwelling) and a quality characteristic (construction product), a quantity (m^2) and a duration (y). In the case of construction products the functional unit refers to the surface area of the construction element (e.g.: external wall, ceiling, etc.) and is expressed as*: 1 m^2 of* *construction element, or 1 piece/item of construction element*. In this case the functional unit contains the specification of the function (e.g.: wall, ceiling, etc.) and a quality characteristic (construction product a quantity (m^2).

For the application of LCA studies in technological components for energy and heat production, the FU usually refers to performance quality of the function, e.g.: energy produced in a specific time unit, expressed as *kWh energy or heat produced,* or one piece/unit within a specific power output.

Lastly, the term 'declared unit' is specific to product LCAs, as stated in EN 15804 [7]. It is used instead of the 'functional unit' if the specific function of a product at the building level is not known. 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.

In the process of modelling the components and assessing the results, both the functional unit and the declared unit can be adjusted for better comprehension, comparison or accuracy.

Cut-off criteria

In LCA practice, it is important to determine which inputs to include (consequently which information to exclude) in the study. Input data is determined using cut-off criteria and is applied based on three data types:

- **Mass:** a cut-off criterion based on mass requires the inclusion in the study of all inputs that contribute more than a specified percentage to the mass input of the modelled product system
- **Energy:** using energy as a criterion requires the inclusion in the study of all inputs that cumulatively contribute more than a specified percentage to the energy input of the product system
- **Environmental relevance**: included inputs should be chosen such that they contribute to more than an additional specified amount of an estimated quantity of certain data of the product system selected for environmental relevance.

Inputs selected during this process are used as elemental flows.

Life Cycle Impact Assessment (LCIA): Impact 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.

In LCIA phase, 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 are quantified. LCIA methods, environmental impact category indicators, and environmental damage indicators are thus challenged by numerous and complex supply chains that span over 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.

The information on environmental impacts is expressed with the impact category indicators of LCIA using characterization factors according to ISO 14044 [9].

In the building sector, EN 15804+A1 [7] contains a core set of pre-determined environmental indicators (Table 5: Impact categories included in the goal and scope of the LCA). 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 5: Impact categories included in the goal and scope of the LCA

Indicator	**Acronym**	**Unit**
Global Warming Potential	GWP	kg. CO_2 eq.
Ozone Depletion Potential	ODP	kg. R_{11} eq.
Photochemical Ozone Creation Potential	POCP	kg. Ethene eq.
Acidification Potential	AP	kg. SO_2 eq.
Eutrophication Potential	EP	kg. Phosphate eq.
Abiotic depletion potential for non-fossil resources	ADPE	kg. Sb. Eq.
Abiotic depletion potential for fossil resources	ADPF	MJ
Water Scarcity Footprint	WSF	m^3 H_2O eq
Additional indicator (optional)		
Total use of renewable primary energy resources	PERT	MJ
Total use of non-renewable primary energy resources	PENRT	MJ
Use of net fresh water	FW	m^3
Hazardous waste disposed	HWD	kg
Non-hazardous waste disposed	NHWD	kg
Radioactive waste disposed	RWD	kg

Descriptions of the indicators are given in DIN EN 15804 +A1 Appendix C [7] norm, as follows:

Global Warming Potential

The GWP indicates how much a fixed amount of a “greenhouse” gas contributes to the greenhouse effect. This causes the infrared radiation emitted by the Earth to be partially reflected back to earth. The increased concentration of greenhouse gases leads to an increased reflection, which contributes to global warming of the earth's surface. The comparative value is CO_2 with the potential of 1, related to 100 years dwell time in the atmosphere. CO_2 is itself a major polluter causing the greenhouse effect and thus the global warming.

Ozone Depletion Potential

The ODP summarises the effect of various ozone-depleting gases, the reference parameter being CFC 11 (Trichlorofluoromethane, CCl_3F). The oxygen is irradiated with aggressive UV light in the stratosphere, producing ozone O_3 as a reaction product. Due to this natural phenomenon only a small part of the UV radiation reaches the earth's surface. Ozone is the absorber of UV radiation and thus occupies a protective function for life on Earth. When the ozone layer is reduced there is a stronger penetration of UV-radiation, connected with increased incidences of skin cancer and cataracts. Since 1995, the production and use of CFCs in the EU forbidden.

Photochemical Ozone Creation Potential

The POCP is related to the effect of ethene (C_2H_4). Intensive solar radiation causes aggressive reaction products, especially ozone, to be formed from nitrogen oxides and hydrocarbons.

Photochemical ozone formation near the ground (so-called summer smog) can cause damage to vegetation and materials. Higher concentrations of ozone are toxic to humans.

Acidification Potential

The AP summarizes all substances that lead to acidification in relation to the effectiveness of SO_2. 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.

Eutrophication Potential

The EP summarizes substances in comparison to the PO_4^{3-}-effect together. Over-fertilization can lead to the accumulation of human-toxic substances in ground and drinking water and in soils. Examples of the effects of over-fertilisation are fish mortality, weakened plant growth or, in case of formation to nitrite, serious toxic consequences for human health.

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 and is based on the concentration reserves and rate of de-accumulation.

Water Scarcity Footprint (WSF)

The water scarcity footprint quantifies the potential of water deprivation, to either humans or ecosystems, and serves in calculating the impact score of water consumption at midpoint in LCA or to calculate a water scarcity footprint as per ISO 14046. It is based on the available water remaining (AWARE) per unit of surface in a given watershed relative to the world average, after human and aquatic ecosystem demands have been met.

Optional indicators

The optional indicators can be used to achieve better comparison with existing datasets of conventional technologies. The use shall be discussed with the partners. Based on the discussion USTUTT chooses and calculates the relevant indicators for further use.

Primary energy consumption

Primary energy consumption measures the total energy demand of a country. 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 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. 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.

Environmental information and databases

LCA databases found in practice represent two types of models: 1- databases consisting partly or mainly of generic models (generic datasets) provided by academics and consultancy firms, e.g.: ecoinvent centre, PE International, EC-JRC; and 2- databases consisting of sector or product specific datasets, e.g.: Environmental Product Declaration (EPD) for building products (e.g.: EPD for plastics, EPD for steel, etc.).

Different creators have developed LCA databases in the past 20 years, offering generic datasets: ecoinvent [15], GaBi ts [1616], DEAM [17], and US-LCI [18].

Generic data (datasets and databases) 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 Europe, EPDs are created based on Product Category Rules (PCRs), and built upon the information provided by company-specific individual foreground data, and partly different generic background data. The level of detail in generic and industry datasets can be very different [19] [20].

The Life Cycle Economics methodology (LCE/LCC)

Life Cycle Economics (LCE) is based on the methodology of Life Cycle Costing (LCC) as defined in the VDI 2884 Guidelines [10]. The economic assessment in the building level will be based on the ISO 15686-5 standard [11] and the DIN EN 16627 norm [12].

The term "Life Cycle Costing" implies the total costs generated by a system during its service life from the operator point of view. The aim of the LCC is to optimize the total costs and yields of a system and of the related activities and processes that arise over its life cycle (Figure 6: Graphic representation of Life Cycle Costs [10]).

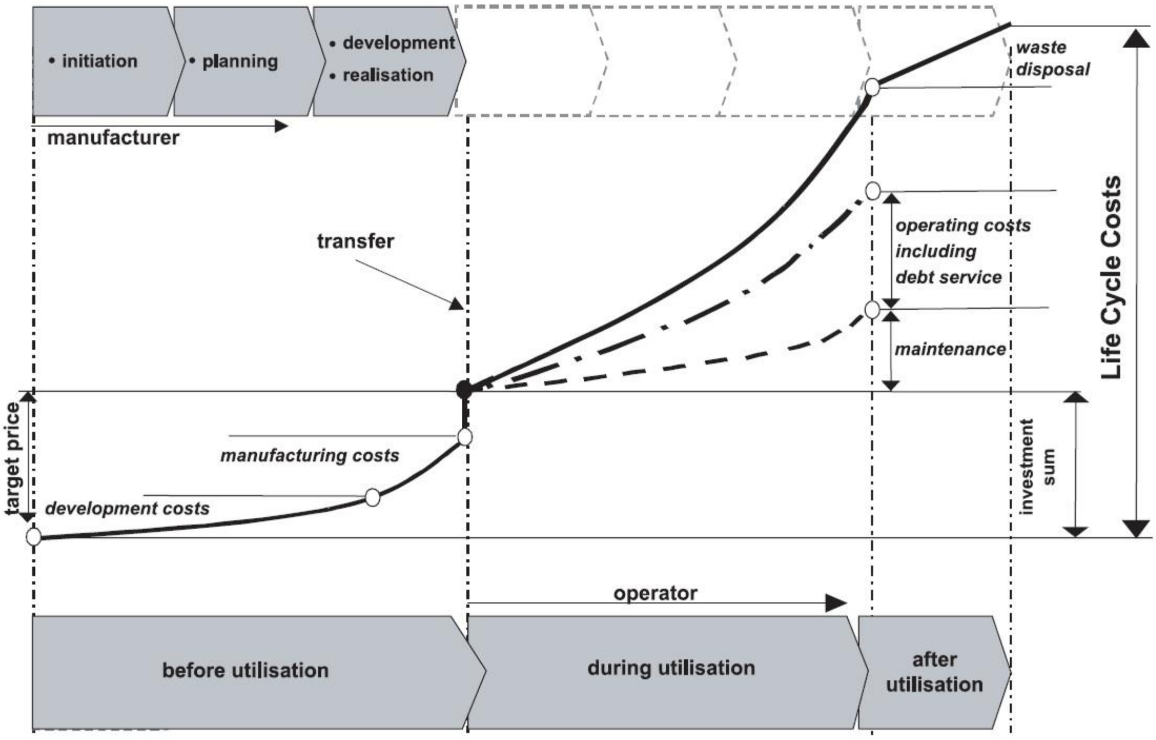


Figure 6: Graphic representation of Life Cycle Costs [10]

VDI 2284 encourages for individual decisions to be taken in the evaluation alternatives for each procurement case regarding the costs and factors which are not quantifiable in monetary terms. Time and effort for the LCC increases with the number of cost types and criteria to be taken into account that is why, what should be taken into account are the costs and factors of equal relevance, i.e. that have a substantial influence on the total costs.

Relevant costs and factors to be taken into account in the decision-making process:

1. Costs which can be taken into account in the "**before utilization**" phase
2. Costs which can be taken into account in the "**during utilization**" phase
3. Costs which can be taken into account in the "**after utilization**" phase

The Life Cycle Economics (LCE) should comply with the framework defined in the goal and scope of the LCA, and in order to accomplish a comprehensible analysis, it will be applied in the same level of detail for all the technologies of WP2.

The cost groups which VDI proposes to be taken into account are given in Annex 1.

Life Cycle Assessment (LCA) in RES4BUILD

In compliance with the RES4BUILD set objectives and the defined specifications of LCA in the previous chapter, the environmental assessment methodology is applied to two levels of detail:

- **LCA for technology components (technology-LCA)**: analysis of the single investigated technologies
- **LCA for integrated systems (integrated systems-LCA)**: analysis of the combined technologies as integrated systems which envisage innovative components (developed innovative technologies in RES4BUILD) for energy production and conventional (market available) technologies in pilot building systems

The LCA examines the technological components in the depicted levels in Figure 7: Technology levels considered for the LCA study in RES4BUILD.

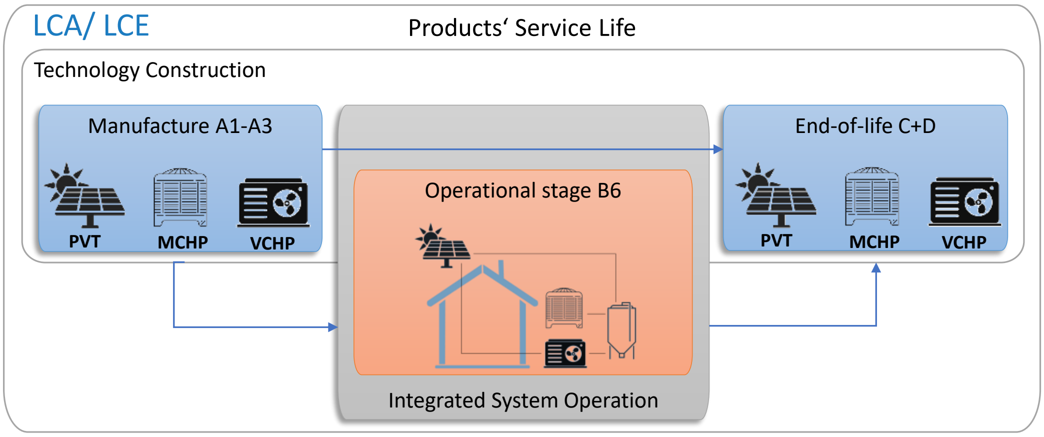


Figure 7: Technology levels considered for the LCA study in RES4BUILD

In the LCA analyses for RES4BUILD, technologies are “decontextualized” from the building, from 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.

In WP6 - Task 6.1, the LCA is applied to investigate environmental impacts of the technologies considered as single components out of the building context. Here, only the environmental impacts coming from the manufacturing (life cycle modules A1-A3) and end-of-life stage (life cycle modules C+D) of the technologies are evaluated without consideration of the operational stage.

In Task 6.2, integrated technology systems are taken into account and simulations are carried out for investigating the performance of the combined innovative technologies with conventional technologies in building pilots. Consequently, the LCA is carried out for the operational phase of the integrated systems and considers the energy consumption of the system (B6 life cycle module).

A general classification of technologies in RES4BUILD is presented in Table 6: List of technologies for the LCA and LCE analysis. Here, the relevance of the technologies to the WPs is addressed, their definition as innovative or conventional types as also the consideration of individual or combined technologies. The assignment as innovative or conventional types sets the conditions of the datasets to be used and/or the necessity of creating own environmental models. The impacts assessment is carried out specifically for each technology in the given life cycle phases (LC-phases) in Table 6: List of technologies for the LCA and LCE analysis.

Table 6: List of technologies for the LCA and LCE analysis

WP	Technology		Innovative/ Conventional		Life cycle phase
			Individual	Combined	
2	Photovoltaic/thermal collector		Innov		A1-A3, C+D
2	Magnetocaloric heat pump (MCHP)		Innov		A1-A3, C+D
2	Vapour-compression heat pump (VCHP)		Conv		A1-A3, C+D
5	Integrated technologies	VCHP	Conv		
		MCHP	Novel	Innov	B6
		Boreholes	Conv		
		Heat pump system	Conv		
		Heat pump pumps	Conv		
		PVT pump	Conv		
		Buffer water tank (BWT)	Conv		

The lifecycle assessment of technological components in RES4BUILD is carried out with the aim to provide environmental profiles for the specific technologies taken into account, which are going to be combined into integrated systems and tested in two pilot buildings. The environmental performance of the technological products is evaluated as separate technologies and in the context of integrated systems for buildings.

The investigated technologies in RES4BUILD attain different characteristics in terms of geometrical scale, function and technical performance, which is why the LCA specifications are set up specifically for each technology. LCA requirements 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.

LCA specifications for technology components

This chapter describes the specifications for the Life Cycle Assessment (LCA) of the technology components considered separately from the building's life cycle. The life cycle phases taken into account are depicted in Figure 8: Technologies considered and life cycle phases analysed for the technology-LCA.

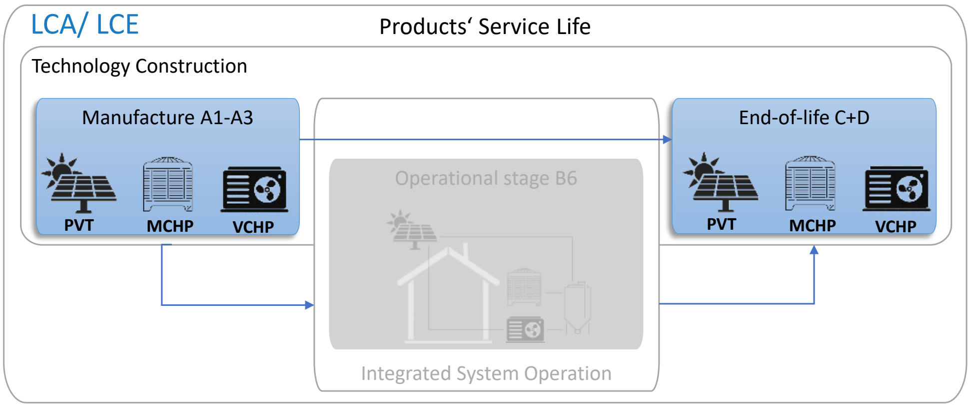


Figure 8: Technologies considered and life cycle phases analysed for the technology-LCA

Goal and scope of assessment of technological components

The focus of investigation lies in the three main technologies in WP2, two of which (PVT and MCHP) are considered innovative technologies, and as such there is presently no life cycle assessment study carried out to provide their environmental impact:

- **Photovoltaic-thermal (PVT) collector**
- **Magnetocaloric heat pump (MCHP)**
- **Vapour-compression heat pump (VCHP)**

The LCA is based on the underlying standards (ISO 14040 [8], ISO 14044 [9], EN 15804 [7]) and international Product Category Rules (PCRs) [20] as well as the guidelines presented in the EeBGuide [5] [6]. The results will feed in the activities of WP5 and WP7 as aggregated data.

This report is addressed to the project partners to whom the results of the environmental assessment are relevant for their ongoing work progress, to the Project Coordinator and the Project Officer for their documentation activities, and to interested stakeholders to whom the environmental impact results represent significant relevance for their market/ industry activities.

Results are going to be directly disclosed to the public, in a report form, through the technology specific fact-sheets and by means of project relevant dissemination activities.

The results of the LCA are intended to be used in the further advancement of the project in WP3, WP5 and WP7, where they will be fed into the simulation platform through a user interface, in order to enable optimization of the technology use and accomplish its designated goal.

The results of the LCA are not intended for focused comparative assertions between products of the same or of similar characteristics (e.g.: no environmental impacts comparison will be carried out between two PVT technologies).

System boundary of assessment of technological components

The investigated technologies are classified as building products, thus the definition of the system boundary for the lifecycle assessment follows the EN 15804 norm [7]. Based on this and on specific PCRs corresponding to the considered technological components, a cradle-to-grave system boundary is considered which includes upstream, core and downstream processes. The considered lifecycle stages include: the manufacturing 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 9: Life Cycle stages taken into consideration for the technology-LCA [7].

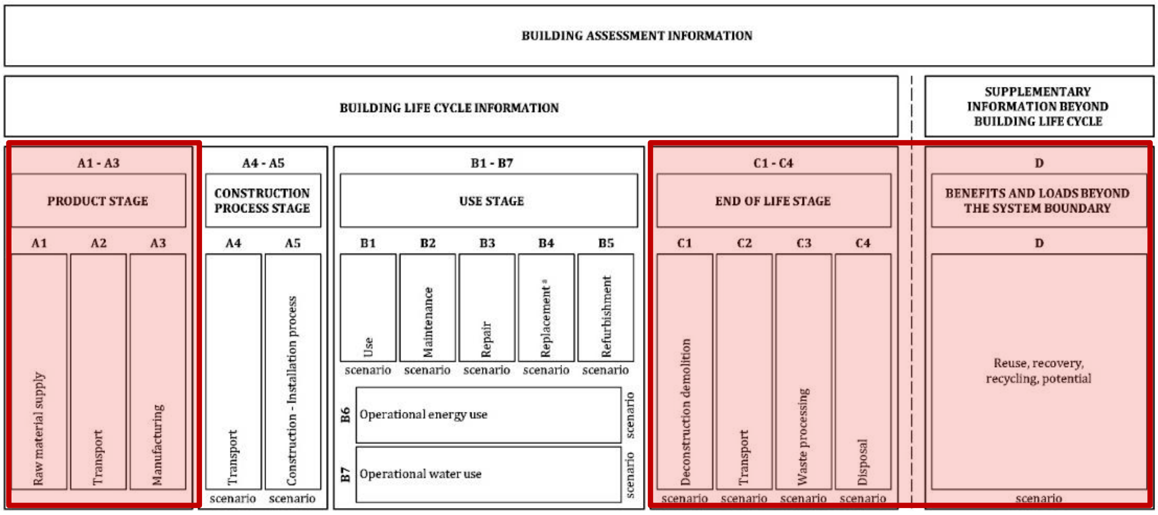


Figure 9: Life Cycle stages taken into consideration for the technology-LCA [7]

For the lifecycle assessment of the technological components, all relevant material and energy flows are recorded. This includes the provision of materials, components and technological assemblies with their assigned technical information, the manufacturing 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 end-of-life (EoL) scenarios. The recorded information comes primarily from the technology providers (MG Engineering for the PVT, DTU for the MCHP and PSYCTOTHERM for the VCHP).

Functional unit of assessment of technological components

Based on the EN 15804 standard [7], 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 [7], specific Product Category Rules (PCR) [21] and technology relevant EPDs are 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.

Cut-off rules of assessment of technological components

The PCR part A for all construction products states that based on provision of information from the technology developers and manufacturers, available data on inputs and outputs must be included in the calculation [2021]. 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.

Impact categories of assessment of technological components

The environmental impact of the technologies during their manufacture and end-of-life (EoL) stages regarding the consumed resources are estimated in environmental impact categories. The assessment is based on the EN 15804+A1 [7], with characterisation factors presented in Appendix C of the standard. Environmental impacts in RES4BUILD are calculated for the impact categories in Table 7: Environmental core indicators for technology-LCA.

Table 7: Environmental core indicators for technology-LCA

Indicator	Acronym	Unit
Global Warming Potential	GWP	kg CO_2-eq.
Photochemical Ozone Creation Potential	POCP	kg. Ethene eq.
Ozone Depletion Potential	ODP	kg. R_{11} eq.
Acidification Potential	AP	kg. SO_2 eq.
Eutrophication Potential	EP	kg. Phosphate eq.
Abiotic depletion potential for non-fossil resources	ADPE	kg. Sb. Eq.
Abiotic depletion potential for fossil resources	ADPF	MJ
Total use of renewable primary energy resources	PERT	MJ
Total use of non-renewable primary energy resource	PENRT	MJ

Data requirements of assessment of technological components

General

The environmental impacts are estimated in the Life Cycle Impact Assessment (LCIA) phase of LCA, based on the Life Cycle Inventory (LCI) of the investigated product. For the preparation of the LCI, quantitative data has to be provided in order to quantify the relevant energy and mass flows and link them together. Data are collected continuously throughout the process of creating the environmental models, making this phase of the LCA an iterative and ongoing one.

Primary data for preparing the LCI is collected from the technology developers and/or investigators in the form of the Bill of Materials (BoM). The BoM is provided in an excel sheet as a list of technological assemblies which are composed of smaller components for which modelling-related data are assigned: material, geographical origin and geometry information. Processing data in this form results in the definition of material and energy flows which are recorded in the LCI. Information on the relevant flows is 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 demand in the utilisation phase in kWh/year.

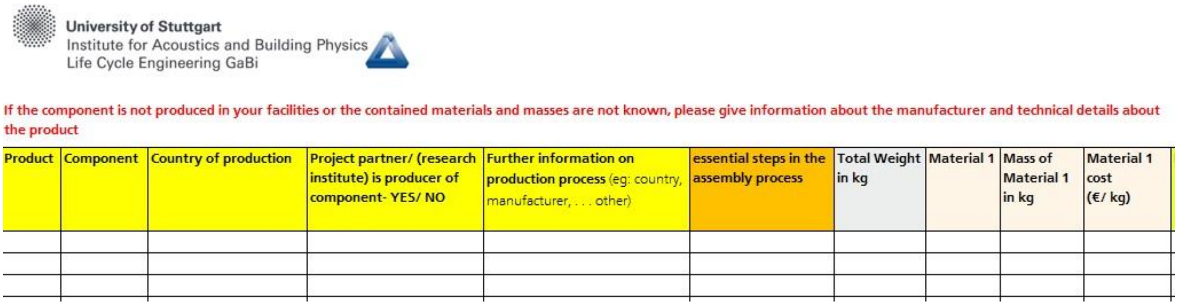
Data should be defined based on geographical, technical and time representativeness.

Data provision from partners

To create the models and estimate the environmental impact all responsible partners provide the necessary data of the innovative technologies in form of a BoM. This is a list of data containing information on all relevant parts and components of the technology.

The outputs of the system express not only the components stated in BoM which create the whole technology, but also the environmental emissions: discharges to air, water and soil. The results from the LCI phase on the output flows are used for further calculations in the LCIA phase for the determination of environmental impacts in the respective impact categories.

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 in order to create the environmental models, is presented in Figure 10: Data collection sheet (DCS) used for collecting technology specific information. The collected information through the DCS is used for the creation of the environmental models of technologies in the environmental software GaBi ts [22].



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 10: Data collection sheet (DCS) used for collecting technology specific information

The information contained in BoM is analysed and organised in such a way to enable easy mapping to input and output flows and prepare them for modelling. Energy flows are represented by generic datasets chosen from the environmental database, containing environmental impact information on energy sources in accordance to the specified origin of technical components. Material flows are represented in the environmental model by region-specific datasets (DSs) depending on the components origin, whereas generic DSs are chosen in the cases where component origin is unknown or unclear.

Data calculation

In order for the data calculation process to be comprehensible, the validation of data collected is necessary. This is done through an iterative communication with the providers of BoM so that the right application of certain data can be approved and data gaps can be clarified and filled. This process is followed by linking the final defined data to unit processes. This phase is carried out by the creator of the environmental model in the modelling software GaBi ts [22]. Data is then linked to the reference flow and necessary adjustments in quantities and units of the input, output and energy flows are made, in order for the final results to be expressed per functional unit (FU) of the system.

Scaling

As described below, the technologies under consideration are at different development/production stages. While the PVT collector and the VCHP are market available or close to market-available products, the (MCHP) is at the prototype stage. For this reason the technologies are not directly comparable. In order to achieve comparability of the prototypes with conventional systems, a scaling of the power and input materials should be carried out.

Throughout the project's progress it has been agreed upon, that the MCHP is so early in its development stages, that no reasonable and meaningful scaling solution can be applied.

Results and recommendations

In the last phase of the LCA study, the results of the LCIA are analysed within the defined framework in the goal and scope of the study. Results are then interpreted in the form of conclusions and recommendations, keeping into consideration that they only show potential and not actual impacts. Through the presentation of value-endpoints, thresholds or risks, the LCA study plays a supporting role in the decision making process for its addressed audience.

LCA specifications for integrated systems

This chapter describes the specifications for the Life Cycle Assessment (LCA) of the integrated systems considered within the building context. The life cycle phases taken into account are depicted in Figure 11: Technologies considered and life cycle phases analysed for the integrated systems-LCA.

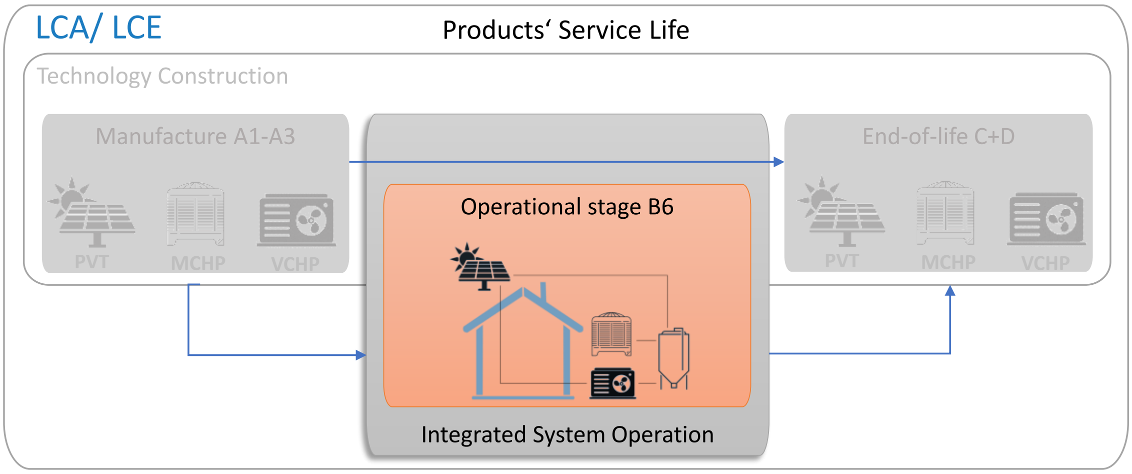


Figure 11: Technologies considered and life cycle phases analysed for the integrated systems-LCA

Goal and scope of assessment of integrated systems

The focus of investigation lies in integrated systems of technologies in two pilot buildings:

- Athens (GR) pilot
- Aarhus (DK) pilot

In *WP3 – Integrated generation, storage and flexibility management*, analysis is carried out on the performance of assembled technologies, while in *WP5 - Design and testing of the prototype systems* on-site tests calculate the performance of the integrated systems as one product. On one hand energy data are delivered from tests, on the other hand, simulations are run aiming to understand present capacity and improvement potential to optimize the system performance.

The focus of LCA in the integrated systems level of detail, is the evaluation of environmental impacts coming for the systems operation. Energy consumption data are extracted from testing in WP5 and simulation-optimization process from WP3, and used as input for the operational phase LCA in WP6.

Results of integrated systems-LCA are addressed to the same audience as the results coming from the technology-LCA. The specification and results of this distinct study are relevant for the project partners for their ongoing work progress, for the Project Coordinator and the Project Officer for their documentation activities, and for interested stakeholders to whom the environmental impact results represent significant relevance for their market/ industry activities.

Results are going to be directly disclosed to the public, in a report form, through the technology specific fact-sheets and by means of project relevant dissemination activities.

The results of the LCA are intended to be used in the further advancement of the project in WP5 and WP7, where they will be fed into the simulation platform through a user interface, in order to enable optimization of the technology use and accomplish its designated goal.

The results of the LCA are not intended for focused comparative assertions between products of the same or of similar characteristics (e.g.: no environmental impacts comparison will be carried out between the RES4BUILD system and a system combination of conventional technologies).

System boundaries of assessment of integrated systems

In integrated systems-LCA, the systems consist of technologies that are analysed in a building pilot context. They are classified as building products, thus the definition of the system boundary for the lifecycle assessment follows the EN 15804 norm [7]. On this basis, a cradle-to-grave system boundary is considered which includes upstream, core and downstream processes. The considered lifecycle stages include: the operational energy use corresponding to life cycle module B6, shown in Figure 12: Life Cycle stages taken into consideration for the integrated systems-LCA [7].

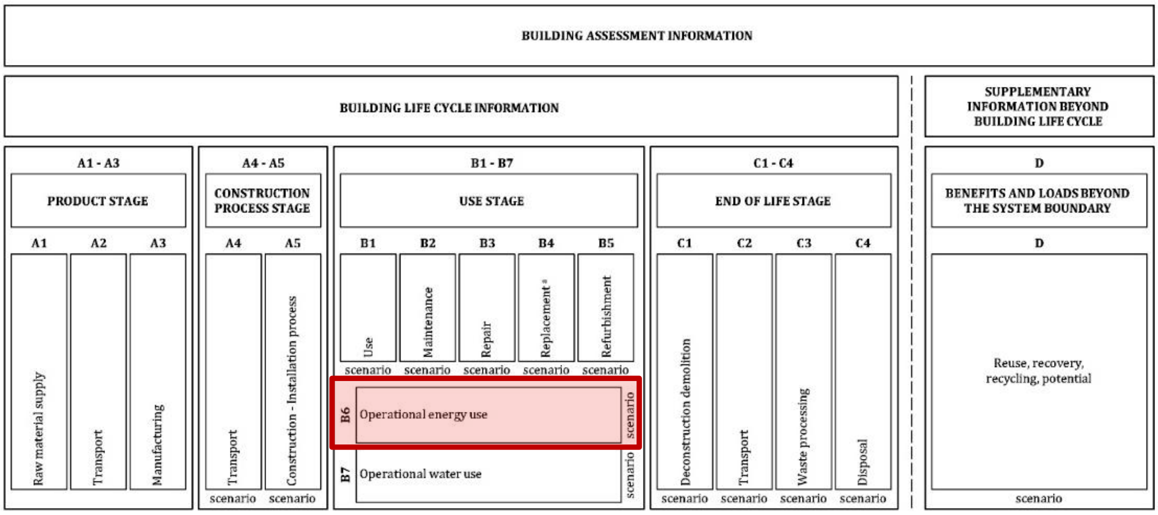


Figure 12: Life Cycle stages taken into consideration for the integrated systems-LCA [7]

For the lifecycle assessment of the integrated technologies in systems, all relevant energy flows are recorded. This includes the provision of energy consumption of the system responding to the climate-specific energy demand and system performance. The recorded information comes from the NCSRD which are WP5 leaders and responsible for the testing of pilots and simulations for performance optimization.

Functional unit of assessment of integrated systems

For the definition of the FU of the integrated system the EN 15804 [7] is used as reference. The FU for the operational phase of the integrated systems is considered: 1 kWh of electricity consumed from the grid for the whole integrated system.

The specifications of technologies contained in the integrated systems are described in the dedicated chapter on LCA-specifications for the integrated systems in the Athens and Aarhus pilots further in the report.

Cut-off rules of assessment of integrated systems

The PCR part A for all construction products states that based on provision of information from the technology developers and manufacturers, available data on inputs and outputs must be included in the calculation [21]. 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.

Impact categories of assessment of integrated systems

Environmental impact of the operational phase of integrated systems is estimated in terms of environmental impact categories, which correspond to the ones defined for the technology-LCA. The assessment is based on the EN 15804+A1 [7], with characterisation factors presented in Appendix C of the standard. Environmental impacts are calculated for the impact categories in Table 7: Environmental core indicators for technology-LCA.

Data requirements of assessment of integrated systems

General

The environmental impacts are estimated in the Life Cycle Impact Assessment (LCIA) phase of LCA, based on the Life Cycle Inventory (LCI) of the investigated product. For the preparation of the LCI, quantitative data has to be provided in order to quantify the relevant energy and mass flows and link them together. All relevant input data are collected after the testing and simulation process of the pilots in WP5 from NCSRD in the form of an excel-sheet. The excel document provides energy related data for the single technologies as well as for the whole system. Information delivered differs between the two pilots since energy production systems respond to two different climate contexts:

- Mediterranean climate – Athens Pilot
- Continental climate – Aarhus Pilot

For the LCI the main relevant data are the energy flows which are delivered already from the partners in terms of quantity: kWh energy/ electricity and COP performance of heat pump.

Generic datasets (DS) are chosen from GaBi ts-Database (DB). These are defined based on geographical, technical and time representativeness.

Data calculation

In order for the data calculation process to be comprehensible, the validation of data collected is necessary. This is done through an iterative communication with the data providers so that the right application of certain data can be approved and data gaps can be clarified and filled. This process is followed by linking the final defined data to unit processes. This phase is carried out by the creator of the environmental model in the modelling software GaBi ts [22]. Data is then linked to the reference flow and necessary adjustments in quantities and units of the input, output and energy flows are made, in order for the final results to be expressed per functional unit (FU) of the system.

Life Cycle Economics (LCE) in RES4BUILD

Based on the LCC methodology in the VDI 2884 Guidelines [10], on the ISO 15686-5 standard [11], on the DIN EN 16627 norm [12], and taking into account the defined specifications of LCA in two levels of detail (technology-LCA and integrated systems-LCA) in the aforementioned chapters, the LCE analysis should correspond to the same levels of detail for consistency of results.

Under this consideration, the economic evaluation is applied for two levels of detail:

- **LCE for technology components (technology-LCE)**: economic analysis of the single investigated technologies
- **LCE for integrated systems (integrated systems-LCE)**: economic analysis of the operation of combined technologies as integrated systems

LCE specifications for technology components

In the first level, economic indicators are evaluated for the singles technologies in regards to their manufacturing stage and the end-of-life (EoL) stage, with no consideration of the building context.

The costs and factors which are defined as relevant for the goal and scope of this study are shown in the following tables:

Table 8: Costs taken into account in the “before utilization” phase, within the goal and scope of this study

Before utilization				
	Provided by the operator	Provided by the manufacturer	Costs Alternative (A)	Costs alternative (B)
General procurement costs				
Procurement price per machine		X		

Table 9: Costs taken into account in the “after utilization” phase, within the goal and scope of this study

After utilisation		
	Costs in EUR	Yields in EUR
Decommissioning		
Disposal of supplies	X	
Dismantling costs	X	
Demolition costs	X	
Recovery of material		
Recycling costs/ re-usage	(X)	

LCE specifications for integrated systems

In the second level of assessment, economic indicators are evaluated for the operation of integrated technologies in systems, in regards to their operational stage.

The costs and factors, which are defined as relevant for the goal and scope of this study, are shown in the following table:

Table 10: Costs taken into account in the “during utilization” phase, within the goal and scope of this study

	Unit	Requirements per operating hour	Costs per unit
Supplies and fuels			
Freight costs/ 1.000 km	kWh	X	X
Energy costs (Electrical power consumption under load)	kWh	X	X
Operating material costs			

The costs marked in (X) represent optional provision.

Decisions on each cost type are based on different data sources:

-Freight costs are based on average data for transport by truck and EU average diesel price.

-Energy costs are built up based on the case studies and the simulations.

-Costs for operating materials are based on statistical percentages according to VDI 2067 (including maintenance)

-Costs for disposal of materials on landfill are based on EU average prices; whereas the recycling potential costs are based on the amounts on recyclable materials and EU average prices for secondary material and scrap.

-Costs for recycling potential are based on the amounts on recyclable materials and EU average prices for secondary material and scrap.

The necessary input data for the LCE analysis on material quantity used on each technology are provided from the respective technology developers.

The economic assessment is not carried out with the aim of evaluating the different cost alternatives that come as a result of application of different materials or component solutions to the technology. LCE is used in this study as a tool to show potential expected costs from the production, use and end-of-life of the technologies taken under consideration.

LCA specifications for the technologies

Specifications for the PVT collector

Description of the technology

The innovative photovoltaic/thermal collector (PVT) - Double Mareco (DM) represents one of the key technologies in the integrated energy system (IES) (Figure 13: The C- PVT collector) (Figure 14: Preliminary PV cell string layout). The innovation lies in the combination of standard photovoltaic (PV) panels and solar thermal collector that allows for simultaneous production of heat and electricity, requiring electrical and hydraulic connection in place. It includes optimized concentrating mirrors to capture sunlight and deliver it afterwards to the PV cells.

This is a stationary concentrating photovoltaic-thermal (C-PVT) collector which uses the patented reflector design “Maximum Reflector Concentration (MaReCo)”, based on Compound Parabolic Reflectors (CPC). High temperatures are reached in this collector due to high stagnation which is why silicone-based encapsulants are applied in order to protect the solar cells from high temperature.

With an energy yield 40-50% higher than that of the combined technologies taken separately for the same total area considered, the DM-PVT collector proves to be highly efficient.

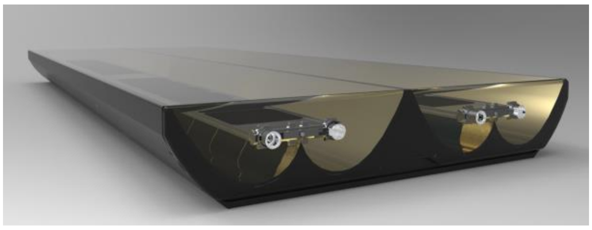


Figure 13: The C- PVT collector [23]

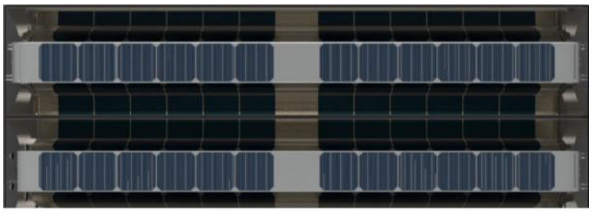


Figure 14: Preliminary PV cell string layout [23]

Function and functional unit definition

As a functional unit for the system is considered 1 item/piece of DM-PVT collector device.

Reference service life (RSL)

According to the Product Category Rules (PCR-2020) for Electricity, Steam and Hot Water Generation and Distribution, the typical service life for solar technologies is considered 30 years [21]. Data on input and output flows are calculated for the defined reference service life. Results represent the technology's reference service life as well.

Data quality

Data on the input flows for the calculation of the environmental impacts are provided from MG Sustainable Engineering [23] who is responsible for the development and research on the Double Mareco PVT collector. Data are provided in an excel spreadsheet in the form of the Bill of Materials (BoM) and specifications on the components' composition are given: amount of pieces, mass (kg), total volume (m^3), total mass (kg) and also the country of origin.

For the installation of the whole PVT collector as one piece technology, MG Engineering assembles the technical components in their facilities in simulation readiness for analysis and testing. The technical components are ordered as prototypes from different manufacturers around the world. Generic data is used for the components of unknown/unclear origin, and proxy data (EPDs) are applied for components whose features are specific to this innovative technology.

The technology is modelled in GaBi 10 version of the software, thus the database used is the professional GaBi database (CUP 2021.2). All data collected in the foreground system were collected at the same level of detail. The data used in both the foreground and background systems represent regional mean data (EU datasets). The input and output flows of all mass and energy flows and the associated processes and data sets are documented.

Life cycle inventory (LCI) of the PVT collector

The Lifecycle Inventory (LCI) presented in this chapter shows input data applied for modelling the PVT collector in GaBi ts. Material and energy flows are part of the LCI and are used to demonstrate the whole lifecycle assessment procedure for the calculation and interpretation of environmental impacts of the technology.

The input data for the LCI of the PVT are collected primarily from the Data Collection Sheet (DCS), which is filled out with specific information on the composition of the product from the technology developers (MG Engineering), and secondly through literature review and research on conventional or existing datasets of similar or same technological products. The material and energy flows relevant for the LCI are summarized below in Table 11: Input quantities for the environmental model of the PVT collector.

Table 11: Input quantities for the environmental model of the PVT collector

Assembly	Sub-assembly	Quantity	Unit
PVT Receiver Big Sun EDGE		**15,8***	**kg**
	PV cells	0,63	m²
	Busbar ribbon	0,125	kg
	Joint tape	0,01	kg
	Sealants	2,02	kg
	Silicon cables	0,01	kg
	Aluminium receiver	5,01	kg
	Insulation foam	0,3	kg
	Insulation rubber	0,004	kg
	Fibre glass mesh	0,01	kg
	Steel screws and fasteners	0,021	kg
	Panel receptacle	0,02	kg
Sub Glass with glue bars		**36,12**	**kg**
	Aluminium bars	7,12	kg
	Glass plate	28,5	kg
	Glue	0,5	kg
Rest components		**11,36**	**kg**
	Middle lock plate	0,052	kg
	Reflector plate	3,55	kg
	Middle mounting block	0,052	kg
	Frame ribs	5,584	kg
	Plastic parts (Gables)	1,8	kg
	Steel screws and fasteners	0,321	kg
Total mass		**62,3**	**kg**

LCA model of the PVT collector – production stage

The LCA model of the DM-PVT is created in GaBi software Version 10 [22], based on the information from the LCI. The model for the production stage is shown in Figure 15: Environmental model of the production stage of the PVT collector in GaBi ts software.

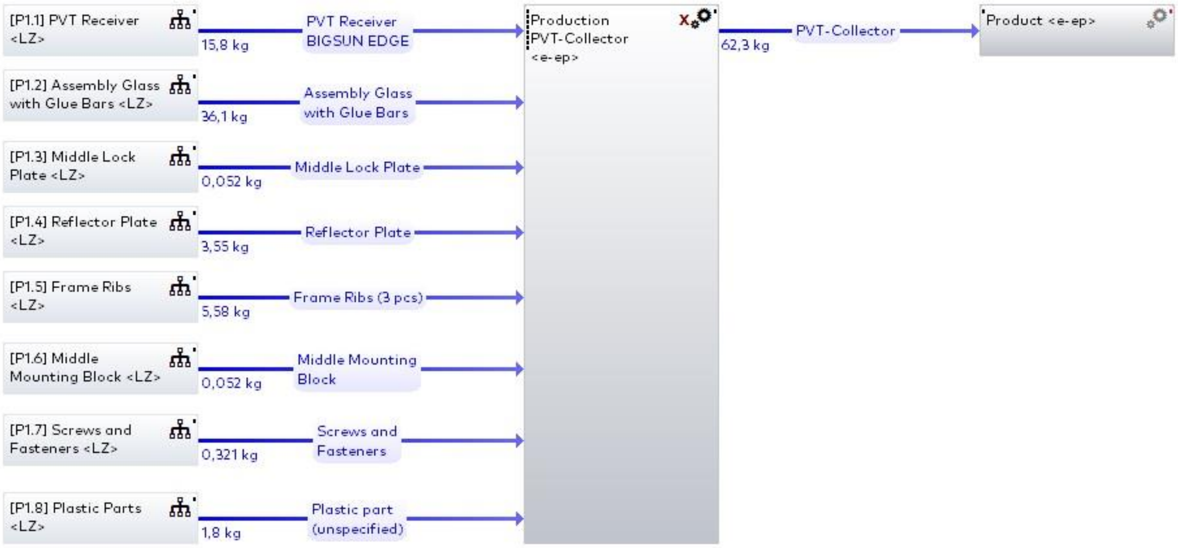


Figure 15: Environmental model of the production stage of the PVT collector in GaBi ts software

The main technological assemblies are represented in the GaBi model by plan-boxes, as depicted in the left on Figure 15: Environmental model of the production stage of the PVT collector in GaBi ts software. Each plan represents the production of that specific assembly based on the material and energy flows provided from the technology developers. The thick blue lines which connect the plans of the assemblies on the left with the main plan-box “Production PVT-Collector” on the right, represent the material flows coming from each technological assembly to create the one-piece final product PVT, as in Table 11: Input quantities for the environmental model of the PVT collector.

Environmental profiles (datasets) used for the production stage of the PVT

Table 12: Background data and environmental profiles for modelling the production stage of the PVT documents the background data and environmental profiles used for modelling the production stage with lifecycle phases A1-A3, using GaBi ts environmental database. The data quality is classified in terms of geographical, time and technological representativeness.

Table 12: Background data and environmental profiles for modelling the production stage of the PVT

Process	**Dataset**	**Representativeness**		
		Geographical	**Time**	**Technological**
Full Square Cells Edge x Deep Blue	mono c-Si Cell, 210µm, 156x156mm, CN production	CN (own DS)	2020-2023	Average, technology mix
Tabbing strip and busbar	Copper Wire Mix (Europe 2015)	EU-28	2015-2020	Average, technology mix
Kapton tape	Elastomer joint tape, polyurethane (EN15804 A1-A3)	DE	2020-2023	Average, technology mix
Wacker Elastosil	Silicone-resin plaster (A1-A3)	EU-28	2020-2023	Average, technology mix
Silicon cables	Cable 1 wire (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix
Aluminium receiver	Aluminium sheet (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix

Receiver insulation	EPDM foam (pipe insulation) (EN15804 A1-A3)	DE	2020-2023	Average, technology mix
O-ring end insulation	Chloroprene rubber (Neoprene) 1kg	DE	2020-2023	Average, technology mix
Fibre glass mesh	Glass fibre mesh	DE	2020-2023	Average, technology mix
Screws and fasteners	Fixing material screws galvanized (EN15804 A1-A3)	DE	2020-2023	technology mix, primary production
Panel receptacle	Acrylnitril-Butadien-Styrol (ABS) - Bauteil	DE	2020-2023	Average, technology mix
Alloy bars	Aluminium sheet (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix
Glass plate	Window glass simple (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix
Glue for post	UV-curing laminating adhesives (approximation)	EU-28	2020-2023	Average, technology mix
Middle lock plate	Aluminium die-cast part	DE	2020-2023	die-casting of brass, production mix, at plant
Reflector plate	Aluminium sheet (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix
Frame ribs	Transparent boards PMMA, extruded (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix
Middle mounting block	Aluminium sheet (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix
Gables	Plastic injection moulding part (unspecific)	DE	2017-2020	Average, technology mix

LCA model of the PVT collector – end-of-life (EoL) stage

The LCA model of the EoL stage of DM-PVT is created in GaBi software Version 10 [22], based on the information from the LCI and is depicted in Figure 16: Environmental model of the end-of-life stage of the PVT collector in GaBi ts software.

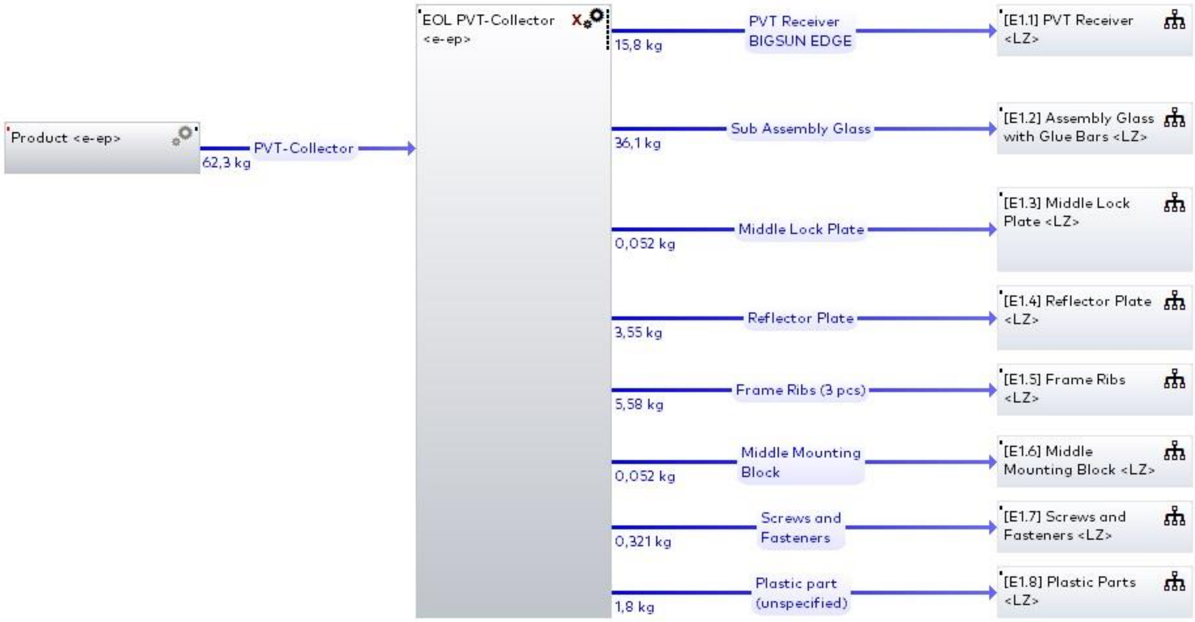


Figure 16: Environmental model of the end-of-life stage of the PVT collector in GaBi ts software

The plan-boxes in the GaBi model of the EoL stage represent the EoL processes for the separate assemblies of the PVT, as depicted on the right on Figure 16: Environmental model of the end-of-life stage of the PVT collector in GaBi ts software. Each plan represents the EoL of that specific assembly based on the material and energy flows provided from the technology developers. The thick blue lines which between the plans of the assemblies on the right and the main plan-box "EOL PVT-Collector" on the left, represent the material flows coming from the whole technology to each assembly as to show the dismantling process of one single product to smaller parts.

Environmental profiles (datasets) used for the end-of-life (EoL) stage of the PVT

Table 13: Background data and environmental profiles for modelling the EoL stage of the PVT documents the background data and environmental profiles used for modelling the EoL stage with lifecycle modules C+D, using GaBi 10 [22]. The data quality is classified in terms of geographical, time and technological representativeness.

Table 13: Background data and environmental profiles for modelling the EoL stage of the PVT

Process	**Dataset**	**Representativeness**		
		Geographical	**Time**	**Technological**
Full Square Cells Edge x Deep Blue	Inert matter (Unspecific construction waste) on landfill	EU-28	2020-2023	Average, technology mix
Tabbing strip and busbar	Non ferrous metals (Copper) (EOL) <LZ>	Own DS	2013-	Average, technology mix
Joint tape, Sealants, Silicon cables, Insulation foam and Insulation rubber	EU-28: Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW) ELCD/CEWEP <t-agg>	EU-28	2006-2015	Average, technology mix
Reciever weld assembly	Light weight materials (aluminium) (EOL) <EoL>	Own DS	2013-	Average, technology mix

Glass fibers	Inert matter (Unspecific construction waste) on landfill	EU-28	2020-2023	Average, technology mix
Steel parts (washers, fasteners, cable lugs)	Steel and Iron materials (EOL)	Own DS	2013-	Average, technology mix
Bars (top, middle, bottom)	Light weight materials (aluminium) (EOL) <EoL>	Own DS	2013-	Average, technology mix
Glass plate	Generic End-of-Life Multi-functionality (glass waste)	EU-28	2020-2023	Average, technology mix
Glue (synthetic)	Disposal of plastics (landfill/incineration, Copy)	EU-28	2020-2023	Average, technology mix
Middle lock plate	Non-ferro metals (others) in waste incineration plant	DE	2020-2023	technology mix, country specific
Reflector plate	Light weight materials (aluminium) (EOL) <EoL>	Own DS	2013-	Average, technology mix
Frame ribs	Polymethylmethacrylate (PMMA) in waste incineration plant	EU-28	2020-2023	Average, technology mix
Middle mounting block	Light weight materials (aluminium) (EOL) <EoL>	Own DS	2013-	Average, technology mix
Screws and fasteners	Steel and Iron materials (EOL)	Own DS	2013-	Average, technology mix
Plastic parts	Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW)	EU-28	2006-2015	Average, technology mix

Specifications for the magnetocaloric heat pump (MCHP)

Description of the technology

The magnetocaloric heat pump developed by the Technical University of Denmark (DTU), is one of the novel technologies that will be applied in the RES4BUILD system. This technology exists for over a decade, but the most recent version of it will be used in the project as an improved technology with a higher COP.

The technology is driven by the magnetocaloric effect (MCE) in which a temperature change of a suitable material is caused by exposing the material to a changing magnetic field. The specific magnetocaloric materials used are $La(Fe,Mn,Si)_{13}H_y$ alloys. This material family allows for optimization of the MCE and of the operating temperature through chemical doping. Thus, a series of materials can be produced, with the MCE tuned to a specific desired temperature range.

As in a vapour compression heat pump (VCHP), where the change in temperature from compression is utilised, the MCHP utilises the temperature change from magnetisation in its thermodynamic cycle. However, in an MCHP there is no gaseous refrigerant, and thus no adverse environmental effect related to leakage of the refrigerant. In addition, the reversibility of the MCE will allow for the MCHP to work at a higher efficiency than the conventional heat pumps.

The highest performing magnetocaloric devices are based on a rotary motion which facilitates a rapid switching of the magnetic field, coupled with accurate control of the flow of heat transfer fluid.

The specific heat pump addressed here has thirteen containers with porous magnetocaloric materials optimised for a specific temperature range. These are successively magnetised and demagnetised by a large rotating magnet (Figure 17: The magnetocaloric heat pump prototype (DTU)). Careful design of the cycle allows heat at a lower temperature to be moved to a higher temperature reservoir, giving a useful heating effect. Accurate control and timing of the fluid flow is realised by solenoid valves.

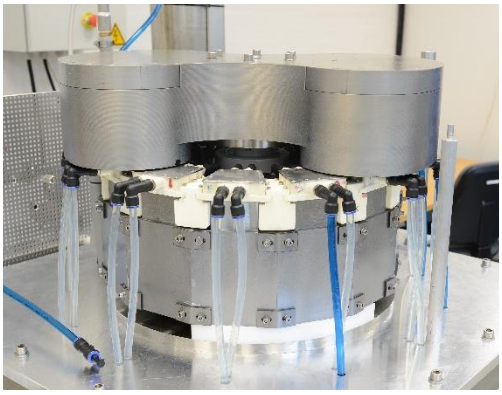


Figure 17: The magnetocaloric heat pump prototype (DTU)

Function and functional unit definition

The life cycle assessment study is based on a piece of technology: 1 item/ piece of MCHP. The results presented here correspond to one single technology, and are not related to its performance (e.g.: energy generated).

Reference service life (RSL)

According to the Product Category Rules PCR 2020 for Electricity, Steam and Hot Water Generation and Distribution, UN CPC 171, 173 2007:08 Version 4.0. RSL is considered to be 20 years [21]. Data on input and output flows are calculated for the defined reference service life. Results are presented for the whole service life as well.

Data quality

Data on the input flows for the calculation of the environmental impacts are provided from DTU who is responsible for the development of the MCHP technology. Data are provided in an excel spreadsheet in the form of the Bill of Materials (BoM) and specifications on the components' composition are given: amount of pieces, mass (kg), total volume (m³), total mass (kg) and also the country of origin.

The technology is modelled in GaBi 10 version of the software [22], thus the database used is the professional GaBi database (CUP 2021.2). All data collected in the foreground system were collected at the same level of detail. The data used in both the foreground and background systems represent regional mean data (EU datasets). The input and output flows of all mass and energy flows and the associated processes and data sets are documented.

Life cycle inventory (LCI) of the MCHP

The Lifecycle Inventory (LCI), and the Lifecycle Impact Assessment (LCIA) is described in this chapter for the MCHP technology in order to demonstrate the whole lifecycle assessment procedure for the calculation and interpretation of environmental impacts of a technology.

The input data for the LCI are collected primarily from the Data Collection Sheet (DCS), which is filled out with specific information on the composition of the product from the technology developers (DTU), and secondly through literature review and research on conventional or existing datasets of similar or same technological products. The material and energy flows relevant for the LCI of the MCHP are summarized below in Table 14*: INPUT QUANTITIES FOR THE ENVIRONMENTAL MODEL OF THE MCHP*.

Table 14: Input quantities for the environmental model of the MCHP

Assembly	Sub-assembly	Quantity	Unit
Magnet assembly		**293,0**	**kg**
	Permanent magnets	77,0	kg
	Magnet housing (yoke)	216,0	kg
Ring assembly		**198,5**	**kg**
	Laminated iron ring	194	kg
	Plastic teeth	2,5	kg
	Spacers	2,0	kg
Regenerator assembly		**4,4**	**kg**
	Tapered regenerator housing	1,0	kg
	Magnetocaloric material	2,8	kg
	Plastic frame	0,6	kg
Table support		**135,0**	**kg**
	Table frame support	70,0	kg
	Base plate	54,0	kg
	Mounting plate	11,0	kg
Flow system		**7,5**	**kg**
	Solenoid valve body	0,5	kg
	Solenoid valve coil	2,0	kg
	Manifold (hot + cold side)	5,0	kg
Others		**54,0**	**kg**
	Plexiglass protection	9,0	kg
	Motor support	12,0	kg
	Motor housing	20,0	**kg**
	Bearing tube flange	13,0	kg
Peripherals		**57,6**	**kg**
	Fasteners Washers Spacers Structural parts Plastic parts		
Total mass		**750**	**kg**

LCA model – production stage of MCHP

The LCA model of the MCHP is created in GaBi software Version 10 [22], based on the information from the LCI. The model for the production stage is shown in Figure 18: Environmental model of the production stage of the MCHP.

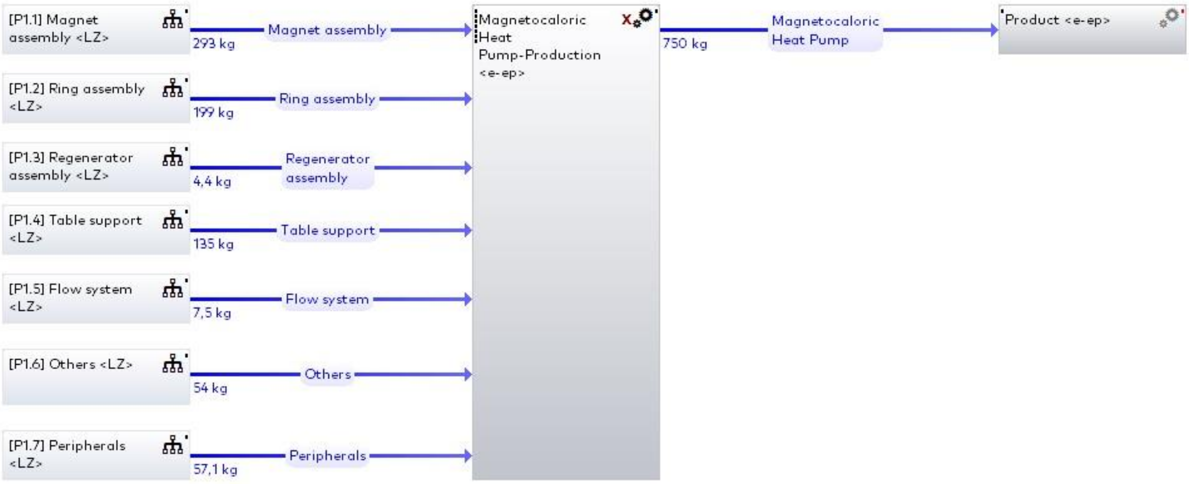


Figure 18: Environmental model of the production stage of the MCHP

The plan-boxes on the left of Figure 18 represent the main technological assemblies of the MCHP. Each plan is a representation of the production of that specific assembly based on the material and energy flows provided from the technology developers. The thick blue lines which connect the plans of the assemblies on the left with the main plan-box "Magnetocaloric Heat Pump-Production" on the right, represent the material flows coming from each technological assembly to create the one-piece final product MCHP, based on material flows in Table 14: Input quantities for the environmental model of the MCHP.

Environmental profiles (datasets) used for the production stage of the MCHP

The background data and environmental profiles used for modelling the production stage with lifecycle phases A1-A3, using GaBi 10 [22] are documented in Table 15: Background data and environmental profiles for modelling the production stage of the MCHP. The data quality is classified in terms of geographical, time and technological representativeness.

Table 15: Background data and environmental profiles for modelling the production stage of the MCHP

Process	Dataset	Representativeness		
		Geographical	Time	Technological
Permanent magnets	CN: Neodymium ts	CN	2018-2021	basic conditions in China
	CN: Dysprosium Production (mass allocated) ts	CN	2018-2021	basic conditions in China
	CN: Iron oxide (Fe2O3) ts	CN	2018-2021	specific conditions in China
Magnet housing (yoke)	Cast iron part (automotive) - open energy inputs	DE	2020-2023	technology mix, country specific conditions
Laminated iron ring	GLO: Steel hot rolled coil worldsteel	GLO	2020-2025	Average, technology mix
Plastic teeth	PC/ABS - Bauteil (XX)	DE (Own DS)	2020-2023	technology mix, country specific conditions

Spacers	Polytetrafluoroethylene granulate (PTFE) Mix	DE	2020-2023	technology mix, country specific conditions
Tapered regenerator housing	Polyamide 6.6 Granulate (PA 6.6) Mix	DE (own DS)	2020-2023	technology mix, country specific conditions
Magnetocaloric material	[P1.3.1] Magnetocaloric material	Own DS (CN, ZA, GLO, EU-28 mix)	2020-2023	specific conditions based on country DS
Plastic frame	PC/ABS - Bauteil (XX)	DE (Own DS)	2020-2023	technology mix, country specific conditions
Table frame support	Steel cast part alloyed (automotive) - open energy inputs	DE	2020-2023	technology mix, country specific conditions
Base plate and mounting plate	Aluminium sheet (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix
Solenoid valve body	Messing (CuZn39)	Own DS (GLO and DE mix)	2020-2023	technology mix, country specific conditions
Solenoid valve coil	Copper pipe mix, bare (A1-A3)	EU-28	2020-2023	Average, technology mix
Manifold (hot + cold side)	Aluminium sheet (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix
Plexiglass protection	PC/ABS - Bauteil (XX)	DE (Own DS)	2020-2023	technology mix, country specific conditions
Motor support and Motor housing	Steel cast part alloyed (automotive) - open energy inputs	DE	2020-2023	technology mix, country specific conditions
Bearing tube flange	Stainless steel part (AISI 304)	EU-28	2014-2024	Average, technology mix
Peripherals (estimation: 60% aluminium, 60% steel, 20% plastics)	PC/ABS - Bauteil (XX)	DE (Own DS)	2020-2023	technology mix, country specific conditions
	EU-28: Aluminium sheet (EN15804 A1-A3) Sphera	EU-28	2020-2023	technology mix, country specific conditions
	Fixing material screws galvanized (EN15804 A1-A3)	EU-28	2020-2023	technology mix, country specific conditions

LCA model – end-of-life (EoL) stage of MCHP

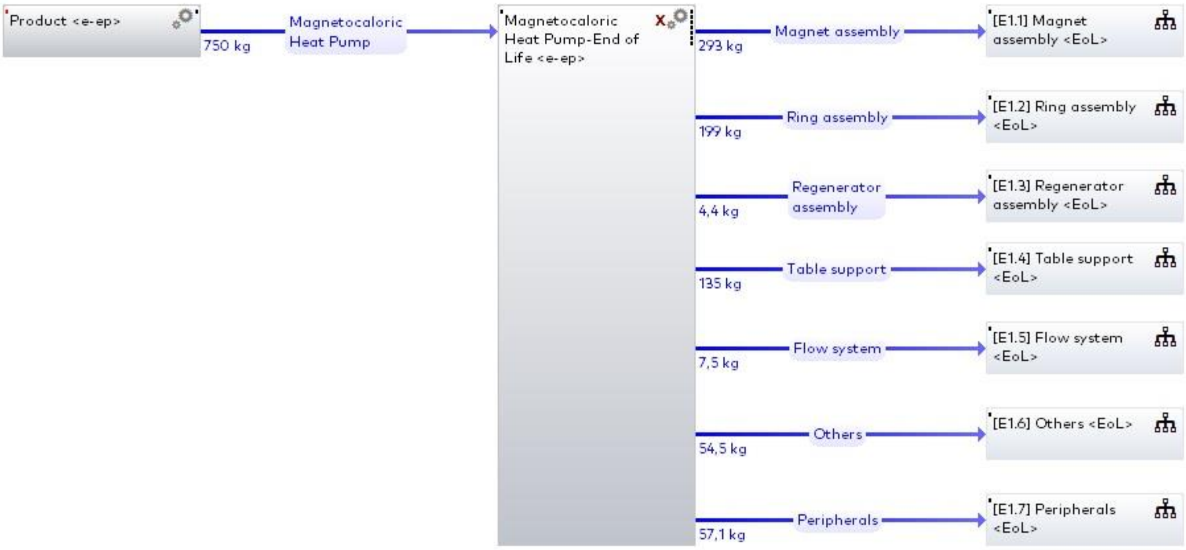


Figure 19: Environmental model of the production stage of the MCHP

The plan-boxes in the GaBi model of the EoL stage represent the EoL processes for the separate assemblies of the MCHP, as depicted on the right on Figure 19: Environmental model of the production stage of the MCHP. Each plan represents the EoL of that specific assembly based on the material and energy flows provided from DTU. The thick blue lines which connect the plans of the assemblies on the right and the main plan-box “Magnetocaloric Heat Pump-End of Life” on the left, represent the material flows coming from the one piece technology to each assembly as to show the dismantling process of one single product to smaller parts.

Environmental profiles (datasets) used for the end-of-life (EoL) stage of MCHP

In Table 16: Background data and environmental profiles for modelling the EoL stage of the MCHP are shown the background data and environmental profiles used for modelling the EoL stage with lifecycle modules C+D, using GaBi 10 [22]. The data quality is classified in terms of geographical, time and technological representativeness.

Table 16: Background data and environmental profiles for modelling the EoL stage of the MCHP

Process	**Dataset**	**Representativeness**		
		Geographical	**Time**	**Technological**
Permanent magnets	Steel and Iron Materials(EOL) (GLO DSs for steel and iron recycling)	Own DS	2013-	Average, technology mix
Magnet housing (yoke)	Ferro metals on landfill	EU-28	2020-2023	Average, technology mix
Laminated iron ring	Steel and Iron Materials(EOL)	Own DS	2013-	Average, technology mix
Plastic teeth and Spacers	Disposal of plastics (landfill/incineration)	EU-28	2020-2023	Average, technology mix
Tapered regenerator housing	Polyamide 6.6 (PA 6.6) (4.5% H2O) in waste incineration plant	EU-28	2020-2023	Average, technology mix

Magnetocaloric material	Ferro metals on landfill	EU-28	2020-2023	Average, technology mix
Plastic frame	Disposal of plastics (landfill/incineration)	EU-28	2020-2023	Average, technology mix
Table frame support	Steel and Iron materials (EOL) <e-ep>	Own DS	2013-	Average, technology mix
Base plate and Mounting plate	Light weight materials (aluminium) (EOL) <e-ep>	Own DS	2013-	Average, technology mix
Solenoid valve body	Non-ferro metals (others) in waste incineration plant	DE	2020-2023	Average, technology mix, country specific
Solenoid valve coil	Non ferrous metals (Copper) (EOL)	Own DS	2013-	Average, technology mix
Manifold (hot + cold side)	Light weight materials (aluminium) (EOL) <e-ep>	Own DS	2013-	Average, technology mix
Plexiglass protection	Disposal of plastics (landfill/incineration)	EU-28	2020-2023	Average, technology mix
Motor support, Motor housing and Bearing tube flange	Steel and Iron Materials(EOL)	Own DS	2013-	Average, technology mix
Peripherals (estimation: 60% aluminium, 60% steel, 20% plastics)	Disposal of plastics (landfill/incineration)	EU-28	2020-2023	Average, technology mix
	Light weight materials (aluminium) (EOL) <e-ep>	Own DS	2013-	Average, technology mix
	Steel and Iron Materials(EOL)	Own DS	2013-	Average, technology mix

Specifications for the vapour-compression heat pump (VCHP)

Description of the technology

The technology of the vapour compression heat pump (VCHP) is investigated by G. Ligeros & SIA OE - PSYCTOTHERM in collaboration with the National Centre for Scientific Research "DEMOKRITOS" (NCSRD) within the context of RES4BUILD project.

The heat pumps of RES4BUILD are developed to match the supply temperatures of typical buildings. Space heating and cooling is delivered to the building through either hot or chilled water, preferably using fan coil appliances that allow to reduce the water temperature at heating mode and thus improve the performance. These temperature levels follow the relevant standards (e.g. EN 14511-2018) and are highlighted next:

- Space heating delivery. Supply temperature of 45 °C, with a return temperature 5 K below that. The supply temperature can be varied within the range of 35-50 °C to account for the flexibility needs.
- Domestic hot water (DHW). Supply temperature of 55 °C that can be varied within the range of 45-55 °C to account for the flexibility needs, which ensures an adequate hot water supply to the users.
- Space cooling delivery. Supply temperature of 7 °C, with a return temperature 5 K above that. The supply temperature can be varied within the range of 7-12 °C to account for the flexibility needs, considering that a temperature difference of 5 K always applies.

The Coefficient of Performance (COP) depends on the temperature levels at the cold and hot sides of the heat pump. A COP up to 6 for a low temperature lift is possible using R454C with a very low Global Warming Potential (GWP) as working medium.

The main advantages of the developed heat pump compared to products in the market are:

- Use of an environmental-friendly refrigerant
- The option to exploit various heat sources resulting to a multi-source unit. This is achieved with the use of 3-way valves and the developed software of the PLC unit.

The heat pump at heating mode can be supplied with heat from either Borehole Thermal Energy Storage (BTES) or ambient air or any other heat source of very low temperature (below 25 °C). Similarly at cooling mode, the possible heat sinks are the ground and ambient air. It can be scaled from few kW (minimum of 6-8 kW of heat) up to few hundred kW, with the latter capacity meeting the needs of very large buildings. Technical specifications of the VCHP are given in Table 17: Technical specifications of the VCHP.

Table 17: Technical specifications of the VCHP

Description	Value	Unit
Dimensions	m	1.5x1.5
Weight (Empty)	kg	90
Weight (Full)	kg	127,6

Function and functional unit definition

The life cycle assessment study is based on a piece of technology: 1 item/ piece of VCHP. The results presented in this fact-sheet correspond to one single technology, and are not related to its performance (e.g.: energy generated).

Reference service life

RSL is based on the Product Category Rules PCR 2020 for Electricity, Steam and Hot Water Generation and Distribution, UN CPC 171, 173 2007:08 Version 4.0. RSL is considered to be 20 years [21]. Data on input and output flows are calculated for the whole defined reference service life.

Data quality

Data on the input flows for the calculation of the environmental impacts are provided from PSYCTOTHERM who is responsible for investigating the VCHP technology. Data are provided in an excel spreadsheet in the form of the Bill of Materials (BoM) and specifications on the components' composition are given: amount of pieces, mass (kg), total mass (kg) and also the country of origin. The technology is modelled in GaBi 10 version of the software, thus the database used is the professional GaBi database (CUP 2021.2). All data collected in the foreground system were collected at the same level of detail. The data used in both the foreground and background systems represent regional mean data (EU datasets). The input and output flows of all mass and energy flows and the associated processes and data sets are documented.

Life cycle inventory (LCI) of the VCHP

The Lifecycle Inventory (LCI), and the Lifecycle Impact Assessment (LCIA) is described in this chapter for the VCHP technology in order to demonstrate the whole lifecycle assessment procedure for the calculation and interpretation of environmental impacts of a technology.

The input data for the LCI are collected primarily from the Data Collection Sheet (DCS), which is filled out with specific information on the composition of the product from the technology developers (PSYCTOTHERM), and secondly through literature review and research on conventional or existing datasets of similar or same technological products. The material and energy flows relevant for the

LCI of the MCHP are summarized below in Table 18. *INPUT QUANTITIES FOR THE ENVIRONMENTAL MODEL OF THE MCHP*.

Table 18. Input quantities for the environmental model of the MCHP

Assembly	**Sub-assembly**	**Quantity**	**Unit**
Scroll compressor		**38,0**	**kg**
Heat exchangers		**32,15**	**kg**
	Condenser	5,8	kg
	Economizer	2,15	kg
	Evaporator-water cooled	6,2	kg
	Evaporator air cooled	18,0	kg
Expansion		**7,55**	**kg**
	Thermostatic expansion valve	0,05	kg
	Receiver	5,0	kg
	Filter	0,9	kg
	Solenoid Valve	0,5	kg
	Three-way Valve	1,1	kg
Control		**5,4**	**kg**
	Inverter - PLC	1,2	kg
	Electric panel	1,5	kg
	Cables	2,7	kg
Sensors		**0,8**	**kg**
	Temperature sensor(s)	0,5	kg
	Pressure sensor(s)	0,3	kg
Water circulation loop		**7,69**	**kg**
	Pump for the condenser loop	1,94	kg
	Pump for the evaporator loop	5,75	kg
Supporting frame		**20,0**	**kg**
Piping		**16,0**	**kg**
	Copper pipes for refrigerant	8,0	kg
	PVC pipes for water	8,0	kg
Total mass		**127,56**	**kg**

LCA model – production stage of VCHP

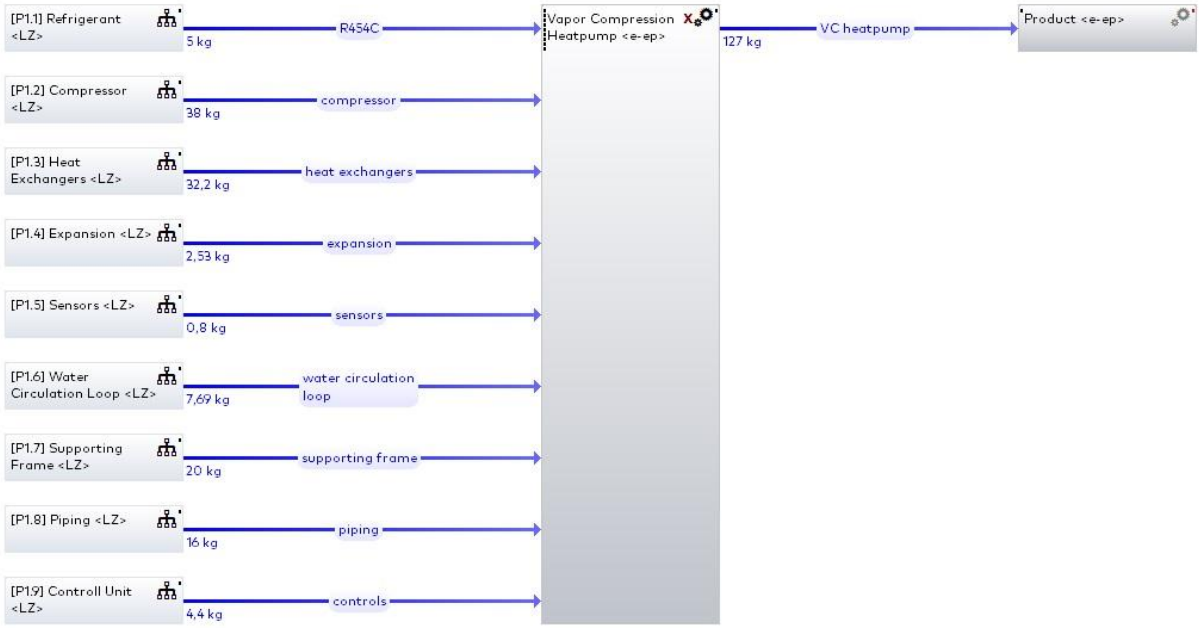


Figure 20: Environmental model of the production stage of the MCHP

The main technological assemblies are represented in the GaBi model by plan-boxes, as depicted in the left on Figure 20: Environmental model of the production stage of the MCHP. Each plan represents the production of that specific assembly based on the material and energy flows provided from the PSYCTOTHERM. The thick blue lines which connect the plans of the assemblies on the left with the main plan-box “Vapour Compression HeatPump” on the right, represent the material flows coming from each technological assembly to create the one-piece final product VCHP, as in Table 18. Input quantities for the environmental model of the MCHP.

Environmental profiles (datasets) used for the production stage of the VCHP

Table 19: Background data and environmental profiles for modelling the production stage of the MCHP documents the background data and environmental profiles used for modelling the production stage with lifecycle phases A1-A3, using GaBi 10 [22]. The data quality is classified in terms of geographical, time and technological representativeness.

Table 19: Background data and environmental profiles for modelling the production stage of the MCHP

Process	Dataset	Representativeness		
		Geographical	Time	Technological
Refrigerant				
R454C	R32 (A1-A3 Ökobaudat)	DE	2018-2022	technology mix, country specific conditions
R1234ze	R1234ze (A1-A3 Ökobaudat)	DE	2018-2022	technology mix, country specific conditions
Compressor		DE	2020-2023	

Cast iron part machined	Cast iron machining (0,05 - 1kg chip)	DE	2017-2020	technology mix, country specific conditions
Plastic part	PC/ABS - Bauteil (XX)			technology mix, country specific conditions
Lubricating oil	Lubricants at refinery	EU-28	2017-2023	Average, technology mix
Heat exchangers				
Copper parts	Copper pipe mix, bare (A1-A3)	EU-28	2020-2023	Average, technology mix
Steel parts	Stainless steel Quarto plate (304)	EU-28	2014-2024	Average, technology mix
Bronze parts	Copper sheet (A1-A3)	EU-28	2020-2023	Average, technology mix
	Tin	GLO	2020-2023	Average, technology mix
Aluminium parts	Aluminium sheet (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix
Expansion				
Cast iron parts	Cast iron machining (0,05 - 1kg chip)	DE	2020-2023	technology mix, country specific conditions
Bronze parts	Copper sheet (A1-A3)	EU-28	2020-2023	Average, technology mix
	Tin	GLO	2020-2023	Average, technology mix
Control				
Electronic component	GLO: Printed Wiring Board 1-layer rigid FR4 with HASL finish (Subtractive method) Sphera	GLO	2020-2023	Average, technology mix
Iron parts	Cast iron machining (0,05 - 1kg chip)	DE	2020-2023	technology mix, country specific conditions
Plastic parts	Polyvinyl chloride granulate (S-PVC) (biobased from corn)	EU-28	2020-2023	Average, technology mix
Copper cable	Cable 1 wire (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix
Sensors				
Steel parts		EU-28	2014-2024	

Plastic parts	Stainless steel cold rolled coil (316) PC/ABS - Bauteil (XX)	DE	2017-2020	Average, technology mix technology mix, country specific conditions
Water circulation loop Pump for the condenser/evaporator loop	Circulating pump 50-250W (EN15804 A1-A3)	EU-28	2020-2023	Average, technology mix
Supporting frame	Stainless steel part (AISI 304)	EU-28	2014-2024	Average, technology mix
Pipes Copper parts	Copper tube; technology mix; market mix, at plant; diameter 15 mm, 1 mm thickness	EU-25	2011-2020	Average, technology mix
Plastic parts	Polyvinyl chloride granulate (S-PVC) (biobased from corn)	EU-28	2020-2023	Average, technology mix

LCA model – end-of-life (EoL) stage of VCHP

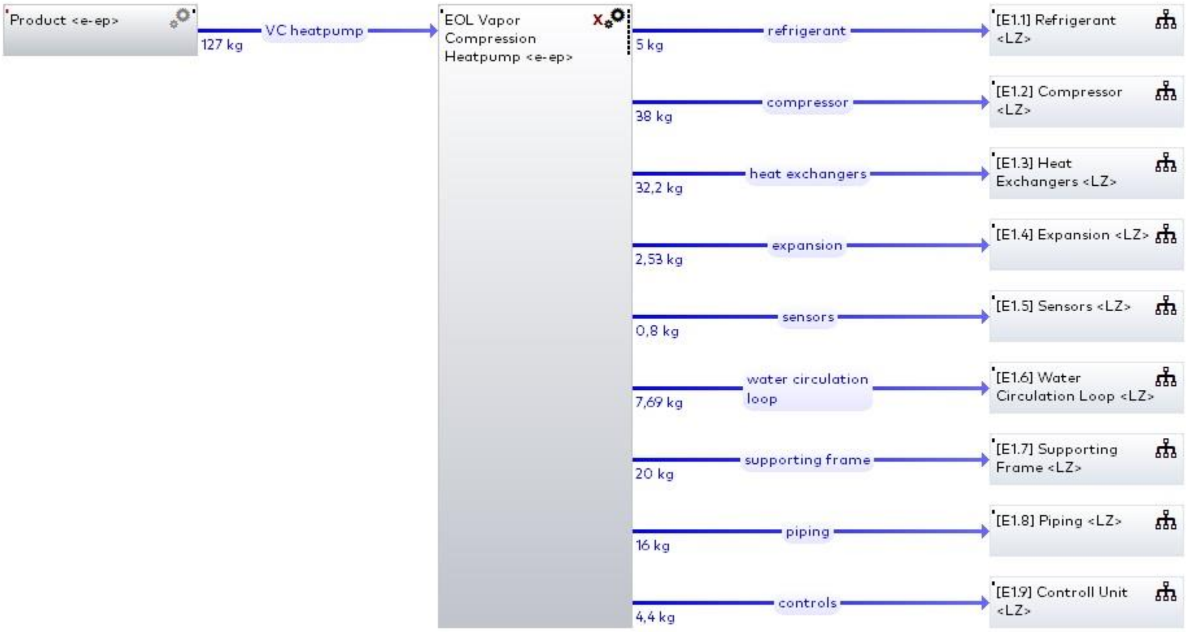


Figure 21: Environmental model of the production stage of the VCHP

The plan-boxes in the GaBi model of the EoL stage represent the EoL processes for the separate assemblies of the VCHP, as depicted on the right on Figure 21: Environmental model of the production stage of the VCHP. Each plan represents the EoL of that specific assembly based on the material and energy flows provided from PSYCTOTHERM. The thick blue lines which connect the plans of the assemblies on the right and the main plan-box "EOL Vapour Compression Heatpump" on the left, represent the material flows coming from the one piece technology to each assembly as to show the dismantling process of one single product to smaller parts.

Environmental profiles (datasets) used for the end-of-life (EoL) stage of VCHP

In Table 20: Background data and environmental profiles for modelling the EoL stage of the VCHP are shown the background data and environmental profiles used for modelling the EoL stage with lifecycle modules C+D, using GaBi 10 [22]. The data quality is classified in terms of geographical, time and technological representativeness.

Table 20: Background data and environmental profiles for modelling the EoL stage of the VCHP

Process	**Dataset**	**Representativeness**		
		Geographical	**Time**	**Technological**
Refrigerant	Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW)	EU-28	2006-2015	Average, technology mix
Compressor				
Cast iron part machined	Steel and Iron materials (EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Plastic part	Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW)	EU-28	2006-2015	Average, technology mix
Lubricating oil	Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW)	Own DS (mixed origin)	2013-	Average, technology mix
Heat exchangers				
Copper parts	Non ferrous metals (Copper) (EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Steel parts	Steel and Iron materials (EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Bronze parts	Non ferrous metals (Copper) (EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Aluminium parts	Light weight materials (aluminium) (EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Expansion				
Cast iron parts	Steel and Iron Materials(EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Bronze parts	Non ferrous metals (Copper) (EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Control				
Electronic component	Populated printed wiring board (after	EU-28	2020-2023	Average, technology mix

	RoHS) in waste incineration plant			
Iron parts	Steel and Iron Materials(EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Plastic parts	Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW)	EU-28	2006-2015	Average, technology mix
Copper cable	Non ferrous metals (Copper) (EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Sensors				
Steel parts	Steel and Iron Materials(EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Plastic parts	Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW)	EU-28	2006-2015	Average, technology mix
Water circulation loop				
Pump for the condenser/evaporator loop	Circulating pump 50 - 250 W (EN15804 C3)	EU-28	2020-2023	Average, technology mix
	Circulating pump 50 - 250 W (EN15804 C4)	EU-28	2020-2023	Average, technology mix
	Circulating pump 50 - 250 W (EN15804 D)	EU-28	2020-2023	Average, technology mix
Supporting frame	Steel and Iron Materials(EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Pipes				
Copper parts	Non ferrous metals (Copper) (EOL)	Own DS (mixed origin)	2013-	Average, technology mix
Plastic parts	Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW	EU-28	2006-2015	Average, technology mix

LCA Specifications for the integrated systems – Athens and Aarhus Pilots

Description of the integrated systems

A set of technologies have been combined in the building level in the form of integrated systems for building energy production. The aim of applying and analysing technologies in systems setting is to investigate energy production performance of technology systems that include innovative components, to analyse energy demand of the system from conventional components, system COP and system energy consumption from the grid. Investigation of the interrelation of innovative and conventional components in energy demand and energy delivery from one component to another, is done for understanding the system potentials in achieving higher COP for buildings energy production and potentials for reducing environmental impact.

In RES4BUILD, integrated systems are investigated in two pilot buildings:

- Athens in Greece, where the pilot building is set up at the lab facilities of NCSRD.
- Aarhus in Denmark, where the pilot is set up at the DTI lab.

Testing of the pilots considers energy values for residential and office types of use, and the energy values (electricity and heating) are extracted from simulations run on the pilots

The main characteristics of the integrated systems in the two pilots are shown in Table 21: Technology components of the integrated systems in two pilots.

Table 21: Technology components of the integrated systems in two pilots

Use types	Athens Pilot and Aarhus Pilot
Residential	Boreholes MWT VCHP MCHP HP (system) BWT - space BWT - solar PVT
Office	Boreholes BWT – space BWT - solar VCHP MCHP HP (system) PVT PVT pump

Acronyms:
MWT - main water tank for hot water
BWT - buffer water tank
VCHP - vapour-compression heat pump
MCHP - magnetocaloric heat pump

The life cycle assessment (LCA) of the integrated systems is applied for the life cycle phase B6 - Operational energy use, as depicted in Figure 12: Life Cycle stages taken into consideration for the integrated systems-LCA [7] in the chapter “LCA specifications for integrated systems”. Environmental impact from manufacturing (life cycle modules A1-A3) and from end-of-life (EoL) (life cycle modules C and D) are not taken into account for the LCA of integrated systems.

Function and functional unit definition

Based on the system boundary defined for the LCA of the integrated systems, the function unit (FU) is considered the energy consumption of the integrated technologies as a system. The FU used is: one kWh energy consumed (electricity) of integrated system. The results calculated correspond to one integrated system, and are related to its performance. The energy consumption presumes energy or electricity demand that the system uses from the electricity grid.

Reference service life

Based on the life cycle phase (B6 module) that is evaluated for the integrated systems and on the goal and scope of the his study as defined in the chapter“ LCA specifications for integrated systems”, the reference service life (RSL) is Data on input and output flows are calculated for the whole defined reference service life.

Data quality

Data on the input flows for the calculation of the environmental impacts are provided from NCSRD who is responsible for investigating the performance of integrated systems as part of WP3 and WP5. Data are provided in an excel spreadsheet and specifications on the systems' main characteristics of performance and energy related information are given: amount of pieces of specific technology components, space energy demand, energy consumed and used by each technology component of the system as also the system COP.

For the LCA, generic datasets (DSs) of the relevant electricity grids are extracted from GaBi 10 database (DB). The database used is the professional GaBi database (CUP 2021.2). The DSs used represent country specific mean data (GR datasets and DN datasets for electricity grid mix). The input and output flows of all mass and energy flows and the associated processes and data sets are documented.

Life cycle inventory (LCI) of the integrated systems in two pilots

The Lifecycle Inventory (LCI), and the Lifecycle Impact Assessment (LCIA) is described here for the integrated systems in the considered pilots, in order to demonstrate the whole lifecycle assessment procedure for the calculation and interpretation of environmental impacts of an integrated system.

The input data for the LCI are collected through an excel-spreadsheet, with specific information on energy quantities consumed and used by the technologies of the integrated systems. Primary data is provided from NCSRD and further input flows (data) are selected through reviewing the GaBi-DB for available datasets that correspond to the country specific energy production conditions. The energy flows relevant for the LCI of the integrated systems are summarized below in Table 22*: INPUT QUANTITIES FOR THE INTEGRATED SYSTEMS-LCA IN THE EXAMPLE OF A RESIDENTIAL BUILDING* for the residential use and in Table 23*: INPUT QUANTITIES FOR THE INTEGRATED SYSTEMS-LCA IN THE EXAMPLE OF AN OFFICE BUILDING* for the office type building.

Table 22: Input quantities for the integrated systems-LCA in the example of a residential building

Athens (GR)				
	Element	**Electricity**		
		Electricity production (kWh)	**Electricity consumption (kWh)**	**Electricity consumed total (kWh)**
Annual	MWT: VCHP		227,1	-1502,5
	MWT: MCHP		0,0	
	MWT: HP system		266,0	
	MWT: HP auxiliaries		34,3	
	spcBWT: VCHP		929,8	
	spcBWT: MCHP		0,0	
	spcBWT: HP system		1117,1	
	spcBWT: HP auxiliaries		168,3	
	VCHP total		1156,9	
	MCHP total		0,0	

	HP system total		1383,1	
	HP auxiliaries total		202,6	
	PVT	1289,3		
	PVT auxiliaries		49,3	
Aarhus (DK)				
Annual	MWT: VCHP		429,5	-1122,2
	MWT: MCHP		0,0	
	MWT: HP system		497,3	
	MWT: HP auxiliaries		59,1	
	spcBWT: VCHP		453,7	
	spcBWT: MCHP		0,0	
	spcBWT: HP system		506,6	
	spcBWT: HP auxiliaries		43,6	
	VCHP total		883,3	
	MCHP total		0,0	
	HP system total		1003,9	
	HP auxiliaries total		102,7	
	PVT	916,8		
	PVT auxiliaries		49,0	

Table 23: Input quantities for the integrated systems-LCA in the example of an office building

Athens (GR)				
Annual	**Element**	**Electricity**		
		Electricity production (kWh)	**Electricity consumption (kWh)**	**Electricity consumed total (kWh)**
	VCHP		879,9	-797,4
	MCHP		0,0	
	HP system		1037,7	
	HP pumps		139,8	
	PVT	1302,4		
	PVT pump		41,4	
Aarhus (DK)				
Annual	VCHP		970,2	-1287,6
	MCHP		0,0	
	HP system		1086,6	
	HP pumps		96,5	
	PVT	911,0		
	PVT pump		45,2	

Acronyms:
MWT – main water tank for hot water
HP – heat pump
BWT – buffer water tank
VCHP – vapour-compression heat pump
MCHP – magnetocaloric heat pump
PVT – photovoltaic/thermal collector
spcBWT – space buffer water tank

Environmental profiles (datasets) used for the operational phase of integrated systems

Table 24: Background data and environmental profiles for modelling the operational stage of the integrated systems documents the background data and environmental profiles used for modelling the operational stage with lifecycle phase B6, using GaBi 10 database [22]. The data quality is classified in terms of geographical, time and technological representativeness.

Table 24: Background data and environmental profiles for modelling the operational stage of the integrated systems

Process	**Dataset**	**Representativeness**		
		Geographical	**Time**	**Technological**
Denmark electricity grid	DK: Electricity grid mix	DK	2017-2023	average country or region specific electricity supply for final consumers
Greece electricity grid	GR: Electricity grid mix	GR	2017-2023	average country or region specific electricity supply for final consumers
European electricity grid mix 2025	Electricity grid mix (2025) (no improvements in sustainability policy)	EU-28	2017-2023	Average, region specific
	Electricity grid mix (2025) (little improvements in sustainability policy)	EU-28	2017-2023	Average, region specific
	Electricity grid mix (2025) (significant improvements in sustainability policy)	EU-28	2017-2023	Average, region specific
European electricity grid mix 2030	Electricity grid mix (2030) (no improvements in sustainability policy)	EU-28	2017-2023	Average, region specific
	Electricity grid mix (2030) (little improvements in sustainability policy)	EU-28	2017-2023	Average, region specific
	Electricity grid mix (2030) (significant	EU-28	2017-2023	Average, region specific

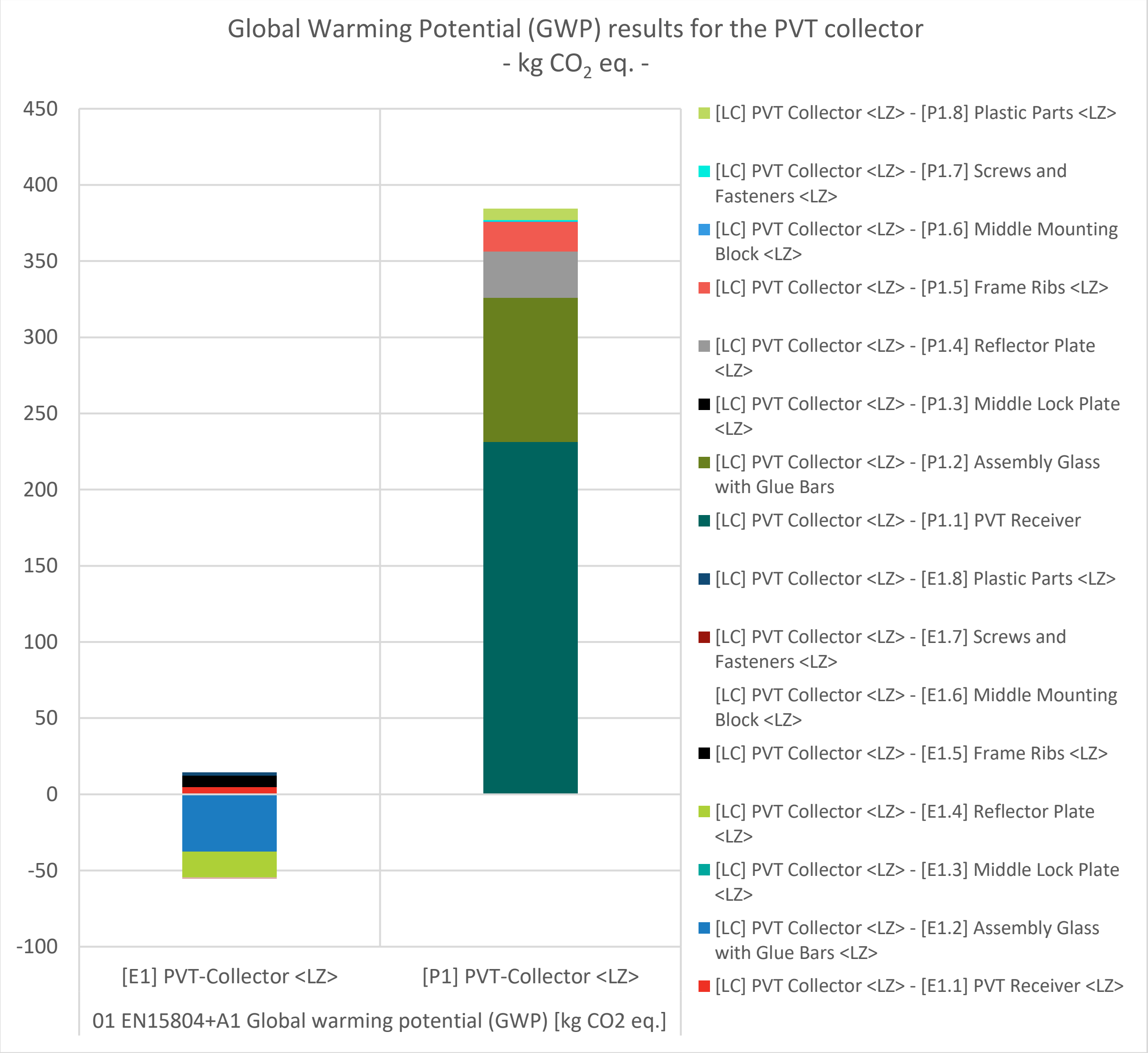
	improvements in sustainability policy)			
	Electricity grid mix (2030) (EU Energy trends report)	EU-28	2017-2023	Average, region specific
European electricity grid mix 2040	Electricity grid mix (2040) (no improvements in sustainability policy)	EU-28	2017-2023	Average, region specific
	Electricity grid mix (2040) (little improvements in sustainability policy)	EU-28	2017-2023	Average, region specific
	Electricity grid mix (2040) (significant improvements in sustainability policy)	EU-28	2017-2023	Average, region specific
	Electricity grid mix (2040) (EU Energy trends report)	EU-28	2017-2023	Average, region specific
European electricity grid mix 2050	Electricity grid mix (2050) (EU Energy trends report)	EU-28	2017-2023	Average, region specific

Environmental assessment results of technology – LCA

In this chapter, only the LCIA results for the Global Warming Potential (GWP) in kg. CO2 eq. for each technology are presented. The LCIA results for the rest of the environmental indicators defined in page 24 based on the EN 15804 + A1, are presented in Annex II.

Impact Assessment (LCIA) of the PVT collector

Figure 22: Results of LCA for the production (A1-A3) and end-of-life (C+D) for the PVT collector



Legend description
[E] – stands for End-of-Life, depicts the End-of-Life models for each assembly and for the whole technology
[P] – stands for Production, depicts the Production models for each assembly and for the whole technology
[LC] - stands for Life Cycle
<EoL> - stands for End-of-Life

Results in Figure 22: Results of LCA for the production (A1-A3) and end-of-life (C+D) for the PVT collector represent the Global Warming Potential (GWP) expressed in kg CO_2 eq., for 1 piece of PVT collector, throughout its whole life cycle (30 years). Environmental impact expressed in GWP during the End-of-Life of the PVT collector are shown in the left half, and impact caused during the production of the technology are shown in the right half part of the chart.

The technology is assessed separately and not in a building context. Results are therefore presented for a 30 year life span, and not for a year time frame.

Highest GWP is caused by the production of the photovoltaic (PVT) receiver - *[P1.1] PVT Receiver*, with an amount of 231,3 kg. CO_2 eq. After the PVT receiver, the highest contribution to GWP comes from the production of the glass and bars assembly - *[P1.2] Assembly Glass with Glue Bars*, with 94,4 kg.

CO_2 eq. The reflector plate - *[P1.4] Reflector Plate <LZ>* and the frame ribs - *[P1.5] Frame Ribs <LZ>* come next, contributing with 30,6 kg. CO_2 eq. and 19,2 kg. CO_2 eq. respectively.

As the results show, highest impacts in the context of GWP are caused by the production of the photovoltaic-thermal receiver which contains the solar cells, and metals (copper, aluminium and steel). The middle lock plate, middle mounting block, screws and fasteners and the plastic parts (PMMA, ABS, rubber, silicon, EPDM, etc.) contribute a very low value of around 8,9 kg CO_2 eq. in GWP. The production stage (A1-A3) of the PVT collector amounts to a total of 384,26 kg CO_2 eq.

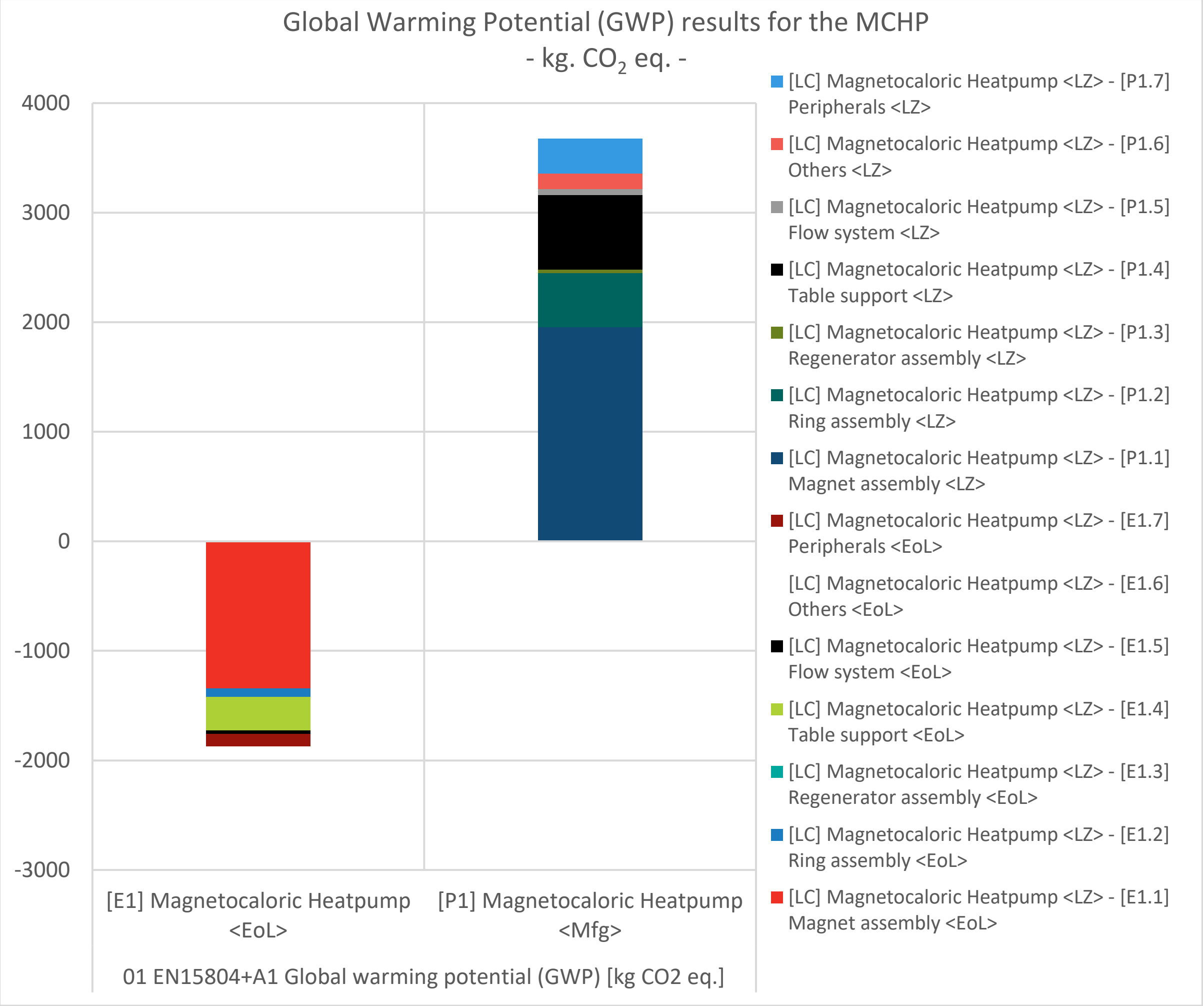
In the End-of-Life stage (C+D modules) negative values to the GWP come from a couple of components (glass and glue bars assembly and reflector plate) due to consideration of recyclability and/or reuse scenarios for the metal components, as well as benefits and credits in energy from incineration of plastics.

In analogy to the production stage, the highest negative value comes from the glass and glue bars assembly - *[E1.2] Assembly Glass with Glue Bars <LZ>*, in the End-of-Life stage as well, with an amount of -37, 6 kg CO_2 eq. For glass a combined recycling and landfill scenario is considered, with 30% of material sent for recycling and 70% in landfill. For the aluminium components in glass assembly, a recycling scenario with 10% material loss is taken into account. Credits are therefore gained for the initial primary material. A high negative value to the GWP, comes also from the reflector plate - *[E1.4] Reflector Plate <LZ>*, with -17,05 kg CO_2 eq. The frame ribs - *[E1.5] Frame Ribs <LZ>,* and the PVT receiver - *[E1.1] PVT Receiver <LZ>,* cause high environmental impacts (GWP values are positive) with 7,6 kg CO_2 eq. and 4,7 kg CO_2 eq. respectively. Since disposal and credits (benefits) from the incineration and recycling are presented together in a summed value, the reason for the positive values during the EoL of the above mentioned materials, lies to low credits gained in the background processes of EoL, which do not compensate for the high impacts.

The End-of-Life of the PVT collector adds up to an amount of -40,7 kg CO_2 eq. Contribution to GWP from the life span of the PVT technology is quantified to 343,6 kg CO_2 eq.

Impact Assessment (LCIA) of the MCHP

Figure 23: Results of LCA for the production (A1-A3) and end-of-life (C+D) for the MCHP



Legend description

[E] – stands for End-of-Life, depicts the End-of-Life models for each assembly and for the whole technology
[P] – stands for Production, depicts the Production models for each assembly and for the whole technology
[LC] - stands for Life Cycle
<EoL> - stands for End-of-Life

Results in Figure 23: Results of LCA for the production (A1-A3) and end-of-life (C+D) for the MCHP represent the Global Warming Potential (GWP) expressed in kg CO_2 eq., for 1 piece of MCHP, throughout its whole life cycle (20 years).

Environmental impact expressed in GWP during the production/ manufacture of the MCHP are shown in the right half, and impact caused during the End-of- Life (EoL) of the technology are shown in the left half part of the chart.

The technology is assessed separately and not in a building context, results are therefore presented for a 20 year life span, and not for a year time frame.

Highest GWP is caused by the production of the magnet assembly - *[P1.1] Magnet assembly <LZ>*, with an amount of 1952,5 kg. CO_2 eq. Second after the magnets, the highest contribution to GWP comes from the production of the table support assembly - *[P1.4] Table support <LZ>*, with 683,9 kg. CO_2 eq. The ring assembly - *[P1.2] Ring assembly <LZ>* and the Peripherals - *[P1.7] Peripherals <LZ>* come next in the list with a contribution of 498,1 kg. CO_2 eq. and 316,1 kg. CO_2 eq. respectively.

As the results show, highest impacts in the context of GWP are caused by the production of the rare earth magnets and cast iron (Magnets= 77 kg and Cast iron= 216 kg) which make up the magnet assembly. The table support, ring and the peripherals (fasteners, washers, spacers etc.) although they contribute in total almost the same amount as the magnet assembly itself, the cause of such high impact can be referred to the high share of metal components in them. The production stage (A1-A3) of the MCHP amounts to a total of 3675,8 kg CO_2 eq.

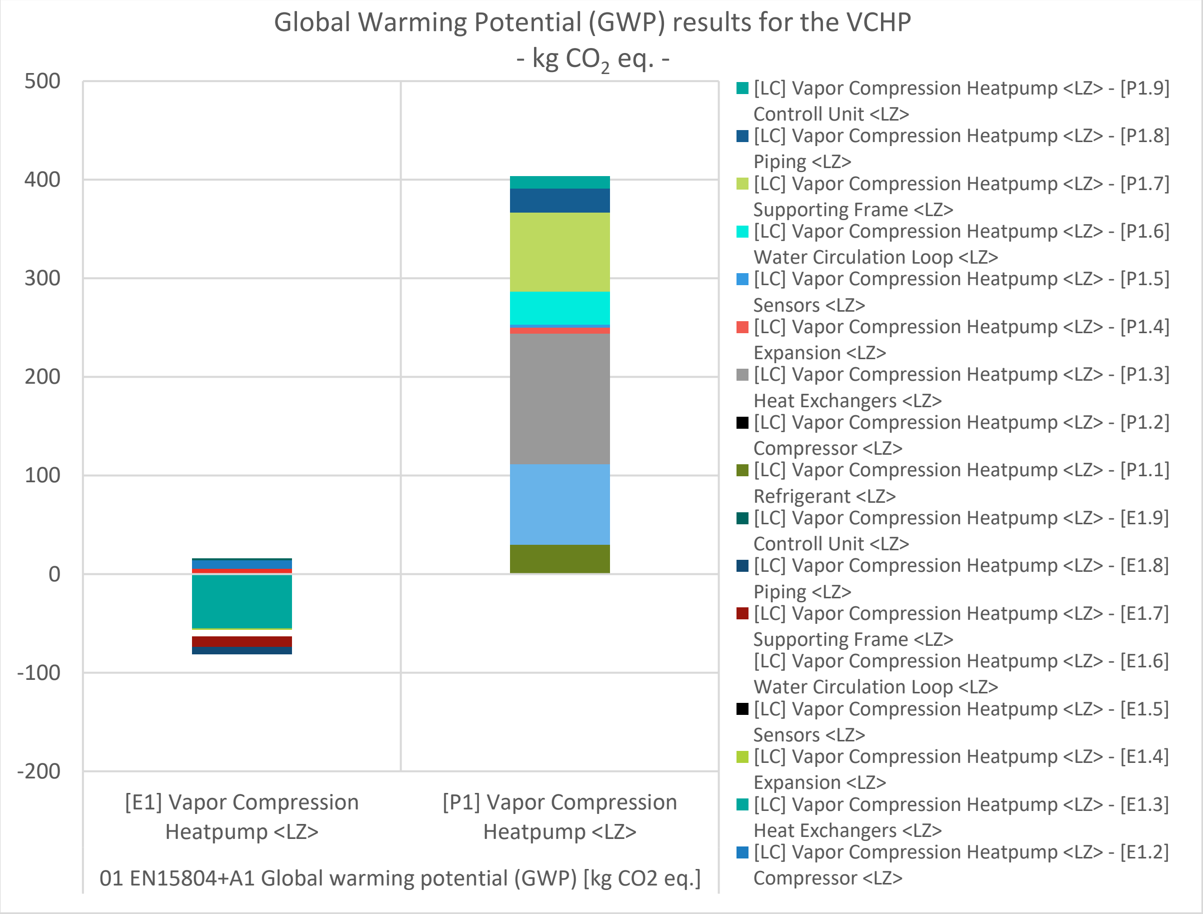
In the End-of-Life stage (C+D modules) mainly negative contributions to the GWP can be observed due to consideration of recyclability and/or reuse scenarios for the metal components, as well as benefits and credits in energy from incineration of plastics.

In analogy to the production stage, the highest negative impact comes from the magnet assembly - *[E1.1] Magnet assembly <EoL>*, in the End-of-Life stage as well, with an amount of -1343,9 kg CO_2 eq. For the magnets, a reuse scenario is considered, while for the cast iron a recycling scenario with 10% material loss is taken into account. Credits are therefore gained for the initial primary material. Second highest negative contribution to the GWP during the End-of-Life of the MCHP, comes from the table support assembly - *[E1.4] Table support <EoL>*, with -311,6 kg CO_2 eq. The ring assembly - *[E1.2] Ring assembly <EoL>,* and the peripherals - *[E1.7] Peripherals <EoL>,* come next, contributing lower benefits during the End-of-Life stage with -74,5 kg CO_2 eq. and -111,9 kg CO_2 eq. respectively.

The End-of-Life of the MCHP adds up to an amount of -1861,4 kg CO_2 eq. Contribution to GWP from the life span of the MCHP technology is quantified to 1814,4 kg CO_2 eq.

Impact Assessment (LCIA) of the VCHP

Figure 24: Results of LCA for the production (A1-A3) and end-of-life (C+D) for the VCHP collector



<u>*Legend description*</u>

[E] – stands for End-of-Life, depicts the End-of-Life models for each assembly and for the whole technology
[P] – stands for Production, depicts the Production models for each assembly and for the whole technology
[LC] - stands for Life Cycle
<EoL> - stands for End-of-Life

Results in Figure 24: Results of LCA for the production (A1-A3) and end-of-life (C+D) for the VCHP collector represent the Global Warming Potential (GWP) expressed in kg CO_2 eq., for 1 piece of VCHP, throughout its whole life cycle (20 years).

Environmental impact expressed in GWP during the production/ manufacture of the VCHP are shown in the right half, and impact caused during the End-of-Life (EoL) of the technology are shown in the left half part of the chart.

The technology is assessed separately and not in a building context, results are therefore presented for a 20 year life span, and not for a year time frame.

Highest GWP is caused by the production of the heat exchangers- *[P1.3] Heat Exchangers <LZ>*, with 132,4kg. CO_2 eq. After the heat exchangers, the highest contribution to GWP comes from the production of the compressor - *[P1.2] Compressor <LZ>*, and the supporting frame - *[P1.7] Supporting Frame <LZ>*, the contribution of which is almost equal: 81,9 kg CO_2 eq. for the compressor and 80,6 kg CO_2 eq. for the supporting frame. Less impact in comparison to the above mentioned assemblies, are caused by the water circulation assembly - *[P1.6] Water Circulation Loop <LZ>,* and the refrigerant - *[P1.1] Refrigerant <LZ>,* with 33,17 kg CO_2 eq. and 29,7 kg CO_2 eq. respectively.

High GWP is caused by the production of the metals (mainly stainless steel and copper) used for heat exchange and make up a high share in the total material composition of the technology. The rest of the assemblies (expansion valves, sensors, piping and control unit) have a low share in the overall weight. Their contribution to GWP for the production stage is less relevant (total of four assemblies equals to 46,0 kg CO_2 eq.) than the above mentioned assemblies compared to the whole technology. The production stage (A1-A3) of the VCHP amounts to a total of 403,7 kg CO_2 eq.

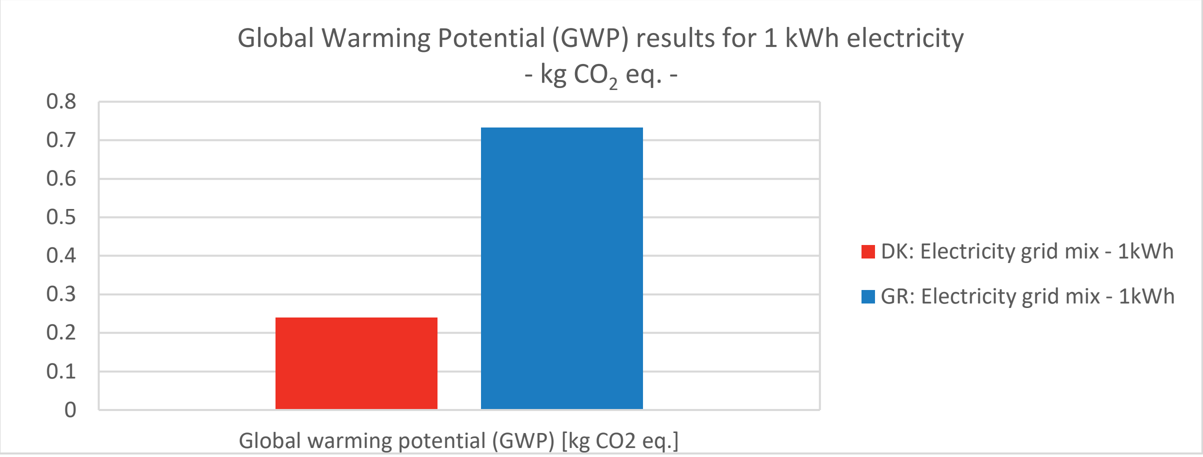
In the End-of-Life stage (C+D modules) mainly negative contributions to the GWP can be observed due to consideration of recyclability and/or reuse scenarios for the metal components, as well as benefits and credits in energy from incineration of plastics.

In analogy to the production stage, the highest negative value comes from the heat exchanger - *[E1.3] Heat Exchangers <LZ>*, in the End-of-Life stage as well, with an amount of -55,3 kg CO_2 eq. Metals used for heat exchange are directed to a recycle/reuse route with 10% material loss and gained credits for the initial primary material. A lower negative value during the End-of-Life of the VCHP, comes from the supporting frame assembly- *[E1.7] Supporting Frame <LZ>*, with -11,0 kg CO_2 eq. On the other hand, the End-of-Life of the compressor - *[E1.2] Compressor <LZ>,* and the End-of-Life of the refrigerant - *[E1.1] Refrigerant <LZ>,* lead to positive impact values. Since disposal and credits (benefits) from the incineration (of refrigerant and plastics in the compressor) and recycling of metals (steel in the compressor) are presented together in a summed value, the reason for the positive values during the EoL of the above mentioned materials, lies to low credits gained in the background processes of EoL, which do not compensate for the high impacts.

The End-of-Life of the VCHP adds up to an amount of -65,7 kg CO_2 eq. Contribution to GWP from the life span of the VCHP technology is quantified to 338,0 kg CO_2 eq.

Environmental assessment results of integrated systems - LCA

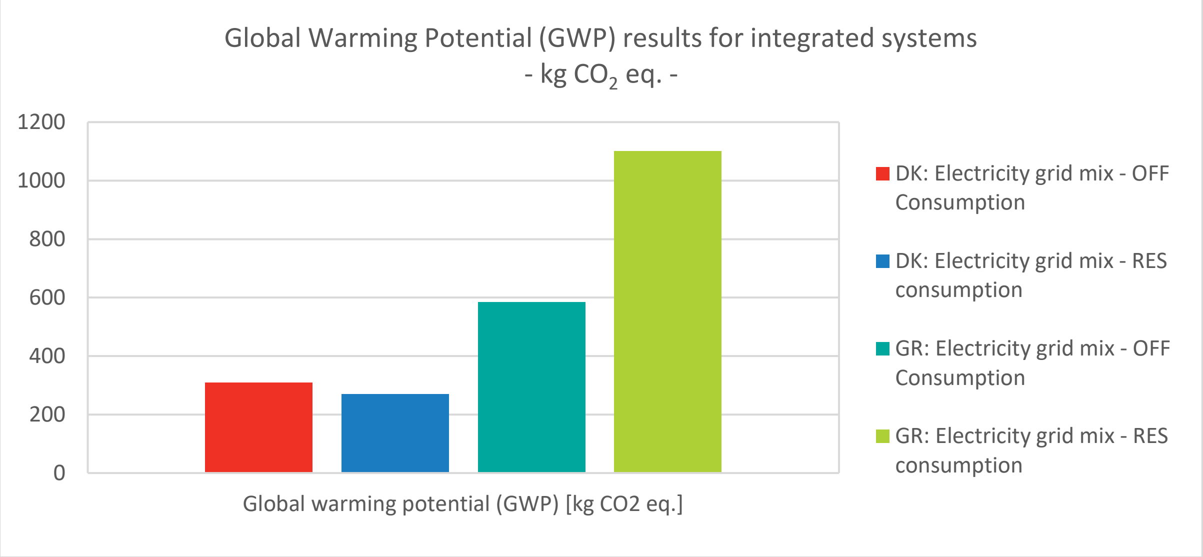
Figure 25: GWP results for 1kWh electricity for the specific countries of the pilots



In Figure 25: GWP results for 1kWh electricity for the specific countries of the pilots are presented the GWP results drawn from the environmental datasets of GaBi-DB, for the electricity grid mix of the two specific countries taken into consideration where the pilot systems are installed. As depicted, the electricity grid mix of Denmark is responsible for less environmental impact in comparison to the electricity grid mix of Greece. The Greek electricity grid mix contributes with 0,73 kg. CO_2 eq. for 1 kWh electricity, whereas the Danish electricity grid mix contributes with 0,24 kg. CO_2 eq. for 1 kWh electricity. The difference in environmental impact between electricity grid mix of both countries, results from the country-specific composition of the energy sources used to generate electricity. The background data on the share of fuels for energy production in each dataset show that the high GWP impact caused by the GR electricity grid mix comes mainly due to high share of lignite (33,95%). In Danish electricity grid mix, hard coal has the highest share (20%) of fuel in the electricity grid mix, which contributes negatively to environmental impact as well, but not in as high share as the share of lignite in the GR grid. As a consequence, CO_2 emissions from lignite in GR electricity grid mix are higher than hard-coal emissions for electricity production in DK grid. The information on electricity supply for different sources and the environmental impact are extracted from GaBi-DB and attached in Annex I.

The environmental impact expressed in GWP for 1 kWh electricity of these regions, is converted to the environmental impact for the energy consumed in the pilots in the next step.

Figure 26: GWP results for the operational phase (B6) of the integrated systems in the pilots



<u>Legend description</u>
DK – Denmark
GR – Greece
RES – Residential
OFF – Office

Where:

Energy consumed RES – GR = 1502,5 kWh annual
Energy consumed RES – DK = 1122,2 kWh annual
Energy consumed OFF – GR = 797,4 kWh annual
Energy consumed OFF – DK = 1287,6 kWh annual

Figure 26: GWP results for the operational phase (B6) of the integrated systems in the pilots shows as expected, that the GWP results coming from the integrated systems-LCA, correspond to the environmental impact of 1 kWh electricity profiles (GR and DK) depicted in Figure 25: GWP results for 1kWh electricity for the specific countries of the pilots for the specific regions separately. Results are given for the energy consumed from the RES4BUILD integrated system in two types of use: residential (RES) and office (OFF).

The integrated system in the residential building type of use, being fed from the Danish (DK) electricity grid mix, is responsible for 269,8 kg. CO_2 eq. *year. The residential type of building using electricity from the Greek electricity grid, contributes with 1100,1 kg. CO_2 eq. *year to the GWP.

The office type of use with energy consumption from the Danish electricity grid mix, causes 309,6 kg. CO_2 eq.*year, while the RES4BUILD integrated system producing energy for the same building type but consuming electricity for the Greek grid mix, is responsible for 583,9 kg. CO_2 eq. *year.

The results of the LCA for the B6 operational phase of the integrated systems in different energy production conditions, and for two building uses are summarized in Table 25: GWP results of the integrated systems- LCA.

Table 25: GWP results of the integrated systems- LCA

	Pilot	
Use type	**DK – Denmark (kg. CO_2 eq.*year)**	**GR – Greece (kg. CO_2 eq.*year)**
RES – Residential	269,8	1100,1
OFF – Office	309,6	583,9

LCIA results in terms of the rest of the environmental indicators defined in page 28, for the four case studies considered here, are presented at the end of the report in Annex III.

RES4BUILD Integrated system vs. conventional solutions

In order for the analysis of environmental impacts of the RES4BUILD integrated system to be more comprehensive, a comparison with a conventional solution is necessary. For the comparison, based on market relevance and business-as-usual scenario, two competing solutions are taken into consideration:

- Conventional solution 1 – Air-source heat pump
- Conventional solution 2 – Gas boiler & AC

Energy related data are simulated in the pilots, for the same use types (RES and OFF), however in this case, the solutions represent conventional widely used technologies for energy production in buildings. The simulations are based on technologies with similar COPs as the technologies in RES4BUILD system. Energy consumption for each building use are extracted from the simulations and multiplied by the respective electricity grid mix datasets of the regions taken into account (GR and DK). In the case of conventional solution 2, where a gas boiler is selected, ready available datasets for gas condensing boilers are used from the environmental database, for calculating the environmental impact of gas consumption.

Table 26: Related gas boiler datasets used for comparison

Process	**Dataset**	**Representativeness**		
		Geographical	**Time**	**Technological**
Operational phase of gas boiler in DK	DK: Gas condensing boiler 20-120 kW (use)	DK	2017-2023	average country or region specific electricity supply

				for final consumers
Operational phase of gas boiler in GR	GR: Gas condensing boiler 20-120 kW (use)	GR	2017-2023	average country or region specific electricity supply for final consumers

An LCA for the operational phase – B6, of the conventional technology solutions is carried out with the aim to identify and indicate the environmental benefits of the RES4BUILD system. The simulations for the calculation of energy consumption are run by NCSRD. Following input data are provided from the simulations.

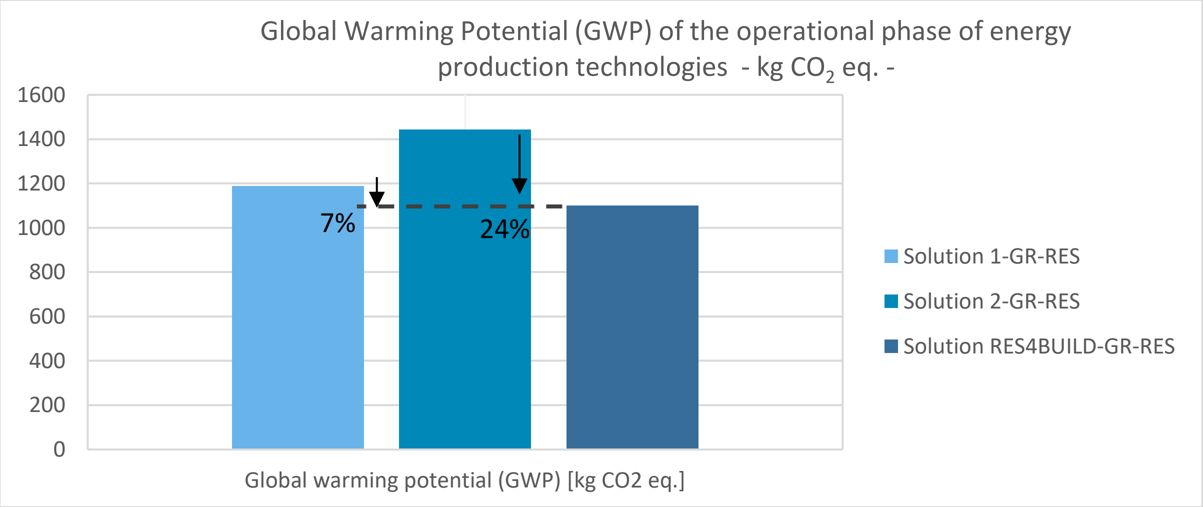
Table 27: Input quantities for the LCA of operational phase of Conventional solutions in two building use types

Solution type	**Country – use type**	**Energy data**		
		Space heat Demand (kWh)	**Electricity consumption (kWh)**	**Gas consumption (kWh)**
Conventional Solution 1	GR - RES	1363,46	1622,13	
	DK - RES	1521,46	1334,02	
Conventional Solution 2	GR - RES	1363,46	631,92	3827,83
	DK - RES	1521,46	0,0	4076,17
Conventional Solution 1	GR - OFF	3225,22	1331,37	
	DK - OFF	4085,37	1485,59	
Conventional Solution 2	GR - OFF	3225,22	374,70	3583,58
	DK - OFF	4085,37	0,0	4539,30

Comparison results

The environmental impact results of the assessment of the conventional solutions are expressed in GWP terms (in kg. CO2 eq.), and are as depicted in the following diagrams.

Figure 27: Environmental impact in GWP for the technology systems considered in Greek-pilot in the example of a residential building



In Figure 27: Environmental impact in GWP for the technology systems considered in Greek-pilot in the example of a residential building are presented the GWP results of conventional solutions 1 and 2 for a residential building under the Greek electricity grid mix, and compared to the RES4BUILD system. Solution 2 with the gas boiler and AC, causes the highest GWP impact with 1442,2 kg. CO_2 eq., while Solution 1 with the air-source heat pump, causes 1187,7 kg. CO_2 eq. The RES4BUILD system is accountant for 1100,1 kg. CO_2 eq. which is 24% less GWP impact in relation to Solution 2 and 7% less GWP impact compared to Solution 1.

Figure 28: Environmental impact in GWP for the technology systems considered in Danish-pilot in the example of a residential building

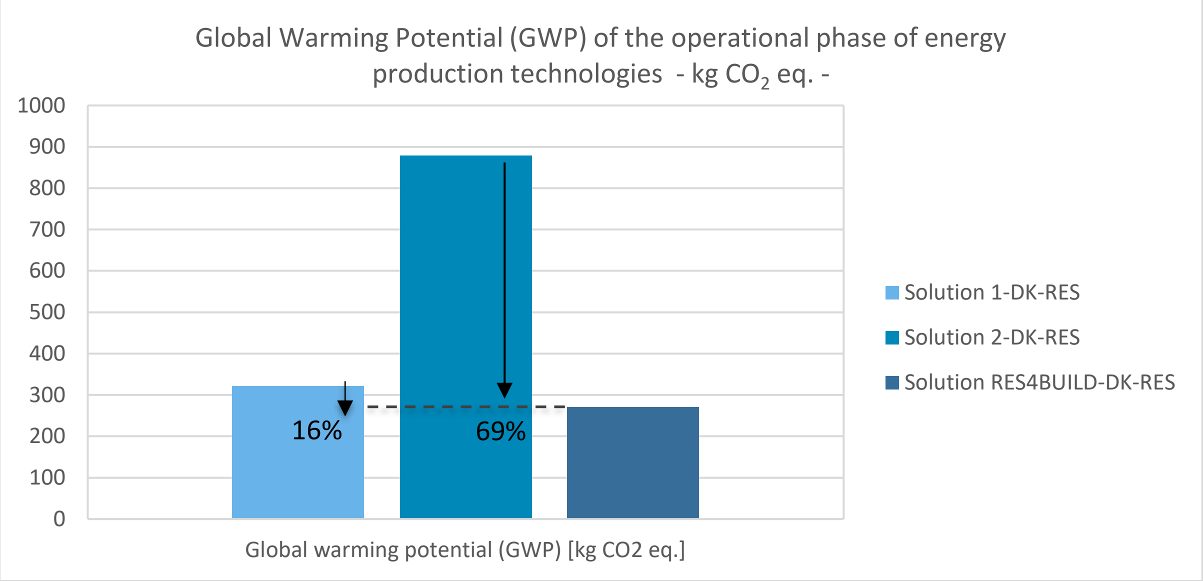
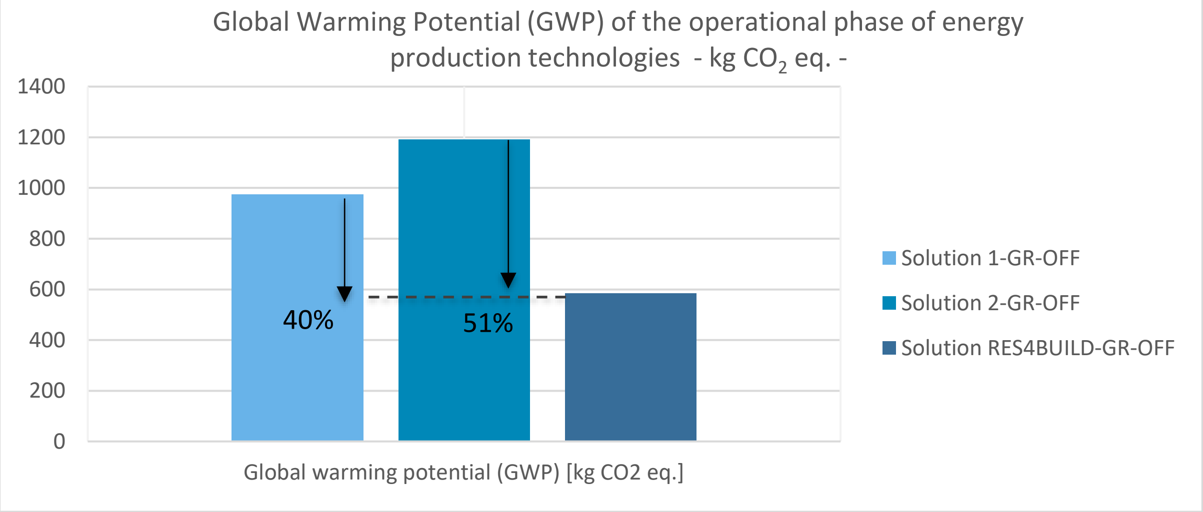


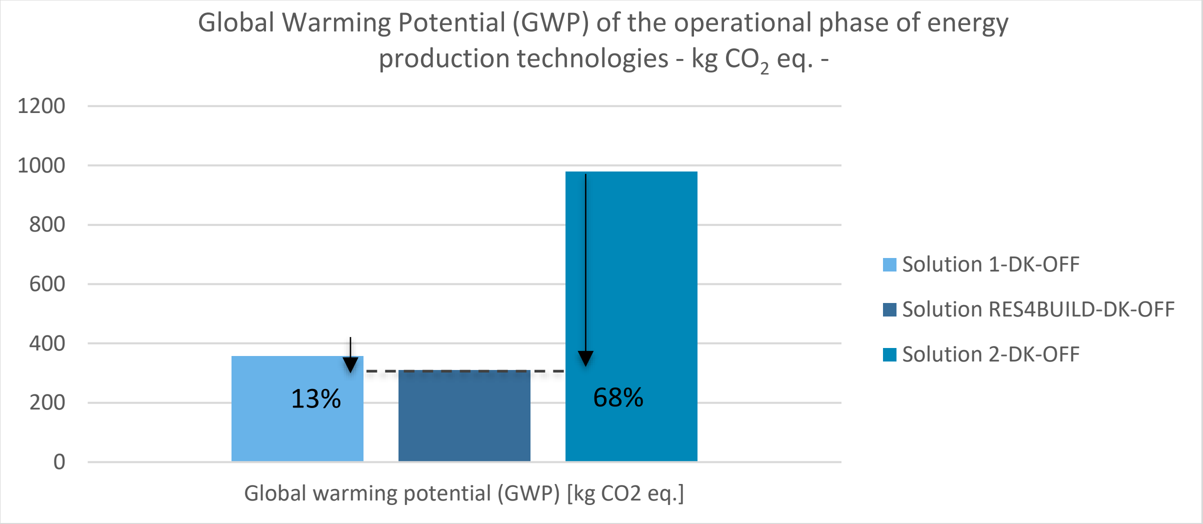
Figure 28: Environmental impact in GWP for the technology systems considered in Danish-pilot in the example of a residential building presents the GWP results from the environmental assessment of the technology solutions for energy production in a residential building, fed from the Danish electricity grid mix. Solution 2 (gas boiler & AC) is responsible for the highest GWP with 879,0 kg. CO_2 eq. and Solution 1 (air-source heat pump) comes second with 320,76 kg. CO_2 eq. The RES4BUILD solution causes less environmental impact compared to Solution 1, and significantly less impact in comparison to Solution 2. RES4BUILD system for this type of building use and under the Danish electricity supply conditions, contributes to GWP with 269,8 kg. CO2 eq., which accounts to 16% less impact than Solution 1 and 69% less GWP impact than Solution 2.

Figure 29: Environmental impact in GWP for the technology systems considered in Greek-pilot in the example of an office building



The environmental impact in terms of GWP are presented in Figure 29: Environmental impact in GWP for the technology systems considered in Greek-pilot in the example of an office building for the technology solutions of energy production in the case of an office building type, receiving electricity from the Greek grid. A technology solution with a condensing boiler and AC, causes 1191,4 kg. CO_2 eq. emissions (Solution 2), while a technology solution considering an air-source heat pump (Solution 1) causes 974,8 kg. CO_2 eq. The highest GWP impact comes in this case from Solution 2 defined by the gas boiler and the AC device. The RES4BUILD solution on the other hand exhibits evidently better in environmental performance regarding GWP impact in comparison to the competing solutions 1 and 2 with 583,9 kg. CO_2 eq. This values indicate 40% less GWP impact from RES4BUILD system in comparison to Solution 1 and 51 % less impact than Solution 2.

Figure 30: Environmental impact in GWP for the technology systems considered in Danish-pilot in the example of an office building



In Figure 30: Environmental impact in GWP for the technology systems considered in Danish-pilot in the example of an office building the GWP impact of the assessed energy-production technologies in buildings are presented, for Solution 1 and 2 as conventional solutions in buildings and compared to the RES4BUILD system, for an office building under the Danish electricity grid conditions. Solution 1 (air-source heat pump) causes 357,2 kg. CO_2 eq. emissions, while Solution 2 (gas boiler & AC) is responsible for the highest GWP impact with 978,9 kg. CO_2 eq. emissions. The RES4BUILD systems causes 309,6 kg. CO_2 eq. indicating 68% less impact compared to Solution 2 and 13% less impact than Solution 1.

Note that, these GWP emissions-reduction results differ slightly to those presented in Deliverable 7.1. This is due to the difference in energy demand profiles for GWP calculations, which for WP7.1 are based on the RES4BUILD - integrated system simulation results, whereas in Task 6.2, GWP calculations are based on the recorded electricity consumption from the electricity grid of the integrated systems in the pilots in WP5. Additionally the GWP emissions factor used in Task 7.1 is a representative single European value in contrast to the country specific electricity environmental profiles (or datasets) utilised in Task 6.2. Even with these differences the general conclusions remain similar.

Economic assessment results

Economic assessment of technologies - LCE

Results of the economic assessment of the separate technologies (PVT, MCHP and VCHP) are presented in Table 23.

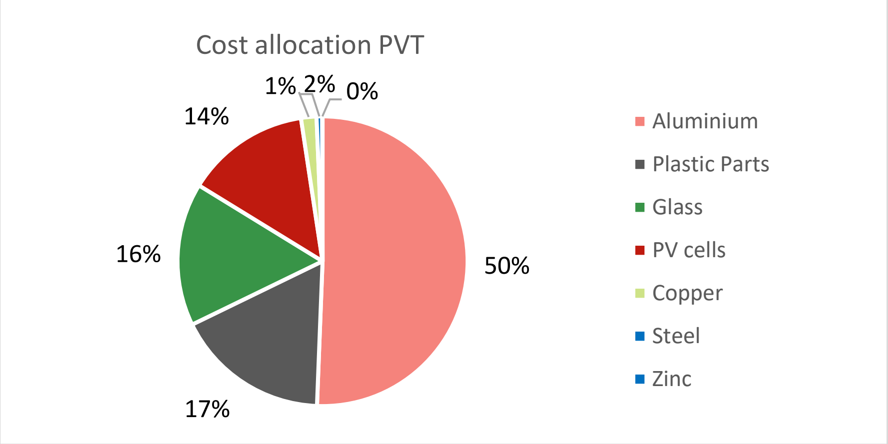
Table 28: Costs of technologies expressed in life cycle phases

Life cycle phase	Costs type	PVT	MCHP	VCHP
before utilisation	Procurement price per machine	134,17 €	1535,34 €	515,47 €
during utilisation	Energy costs residential (1,000 kWh heating and 1.000 kWh cooling)	-	-	111,54 €
	Energy costs office (1,000 kWh heating and 1.000 kWh cooling)	2,01 €	-	106,35 €
	Operating materials costs (yearly)	2,01 €	-	12,89 €
after utilisation	Disposal costs	0,58 €	7,7 €	1,56 €
	Recycling potential	-19,14 €	-448,63 €	-76,38 €
Total		119,67 €	1094,41 €	671,44 €

As depicted in Table 23, there is no available costs data on every life cycle phase for all three technologies equally. The VCHP is a market available technology which is why statistical and generic cost data are available for all the life cycle phases taken into account. The PVT collector, although it is a prototype technology investigated in RES4BUILD under new research conditions, it contains technological components which are market available, and allows in this way to be economically assessed based on statistical cost data. The MCHP is on the other hand a completely new technology, being investigated in RES4BUILD not only for its performance under specific research conditions, but represents a new BoM which has to correspond to the requirements of the research questions raised throughout the project. Therefore, being a prototype technology there are no available statistical or research based cost data to support the economic assessment of all the life cycle phases of this technology with the LCE specifications in this study. Only the available data for the given life cycle phases of the MCHP are therefore taken into consideration, and a sum cost is calculated under this limitation.

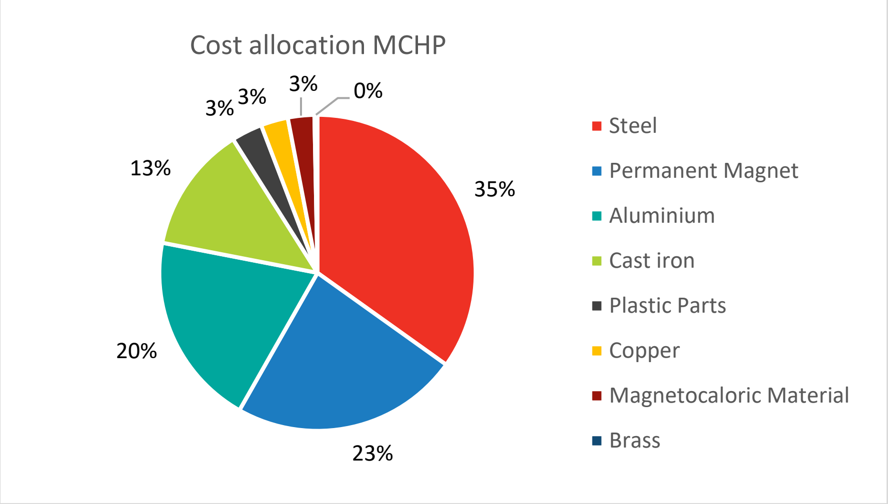
An allocation of costs on material composition of the technologies is presented in the following figures.

Figure 31: Allocation of costs based on material composition for the PVT



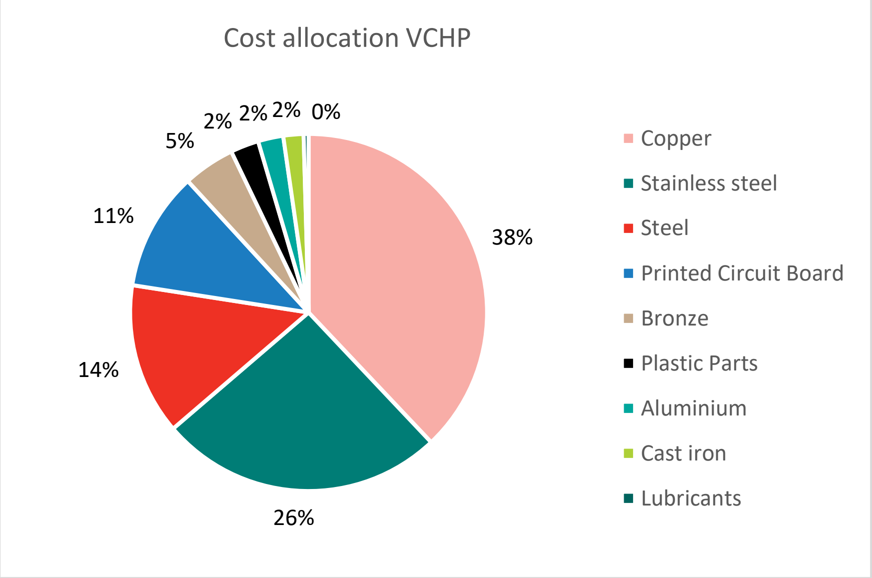
In the PVT, the highest costs come from the aluminium parts, considering all life cycle phases, whereas the procurement price per machine depict the highest value within the life cycle costs (134,17 €). Second to aluminium parts in terms of cost expenditure, are the plastic parts, and after them the glass of the receiver and the PV cells. Copper parts make up a very small part of the life cycle costs, while the rest of materials (steel and zinc) share less than 2% in the total costs of the technology (Figure 31: Allocation of costs based on material composition for the PVT).

Figure 32: Allocation of costs based on material composition for the MCHP



In the MCHP, the highest costs come from steel parts, whereas the procurement price per machine depict the highest value within the life cycle costs (1535,34 €). Second to steel parts in terms of cost expenditure, are the permanent magnets, and after them the aluminium and the cast iron element. Copper and plastic parts make up around 3% each of the total life cycle costs, while the rest of materials (magnetocaloric material and brass) share less around 3% in sum in the total costs of the technology (Figure 32: Allocation of costs based on material composition for the MCHP).

Figure 33: Allocation of costs based on material composition for the VCHP



In the VCHP, the highest costs come from copper elements, whereas the procurement price per machine depict the highest value within the life cycle costs. Second to copper parts in terms of cost expenditure, are the stainless steel parts, and after them the steel and the PCR (Printed Circuit Board). Bronze parts have a share of 5% in the total costs, while plastic parts, aluminium parts and cast iron make up around 2% each of the total life cycle costs. The rest of materials (lubricants) share a very small amount of expenditure in the technology’s life cycle costs.

The share of costs in the technologies from each material part, is dependant from the materials’ price and from the share of materials (kg) in the technology composition.

Economic assessment of integrated systems - LCE

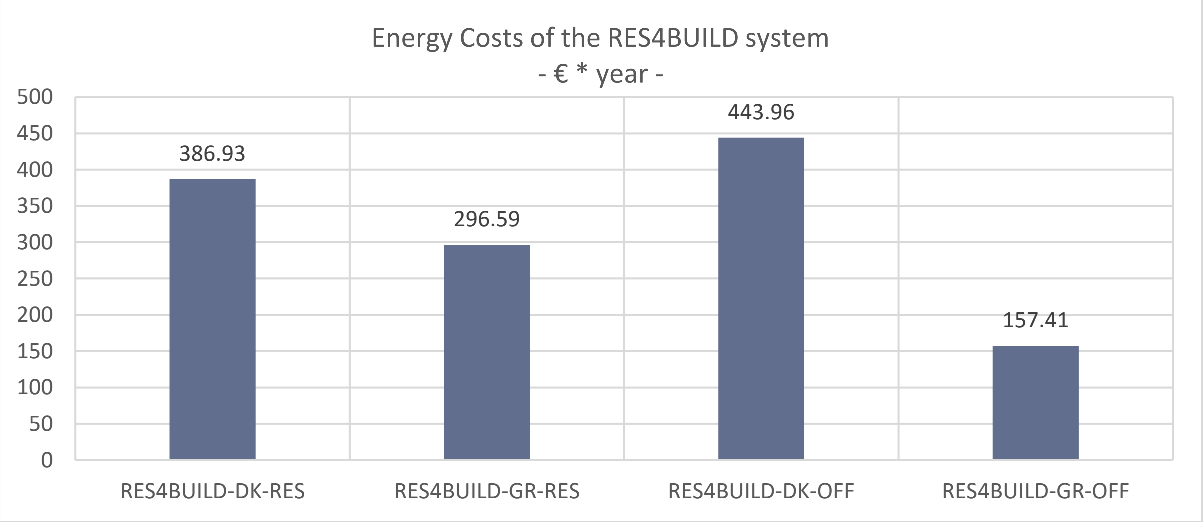
The economic assessment for the RES4BUILD integrated system, takes into account the operational phase of the system in terms of energy consumed in each pilot building. The cost information are extracted from the electricity price indexes published by EUROSTAT in 2021 [24] for European countries. The prices taken into account refer to the 2nd half of 2021, and include taxes as well. Prices are annually presented and indicate costs for medium size households. The currency of electricity price is given in euro (€) and refers to a kilowatt-hour (kWh) energy consumed. The cost information used for the integrated systems-LCE are presented in Table 29: Electricity prices for 2021 of the countries taken into account for the pilots.

Table 29: Electricity prices for 2021 of the countries taken into account for the pilots

GEO (Labels)	Electricity price – 2021 (€/kWh)
Denmark	0,3448
Greece	0,1974

The results of the economic assessment of integrated systems in the Greek and Danish pilots are presented in Figure 34: Electricity consumption costs of the RES4BUILD system in the GR and DK pilots in the example of a residential and an office building.

Figure 34: Electricity consumption costs of the RES4BUILD system in the GR and DK pilots in the example of a residential and an office building.



Legend description
DK – Denmark
GR – Greece
RES – Residential
OFF – Office

The electricity consumption data provided from NCSRD on each pilot case, are converted in economic terms, by multiplying the quantities of electricity consumed per each case with the respective electricity prices of the regions considered. In Figure 34: Electricity consumption costs of the RES4BUILD system in the GR and DK pilots in the example of a residential and an office building. are depicted the costs of the integrated RES4BUILD system as standalone results.

In order to analyse the economic benefit of the RES4BUILD system, the economic assessment presented above, has to be compared to the costs of conventional technology solutions. The RES4BUILD system is therefore compared to the Solutions 1 and 2 defined in the chapter *"RES4BUILD integrated system vs. conventional solutions",* in regards to annual energy costs.

Comparison results

For comparing the RES4BUILD integrated system with the conventional technologies taken into consideration as BAU (business-as-usual) solutions in the pilots, other than electricity prices for the regions where the pilots are tested, the prices of natural gas have to be taken into account for Solution 2 in which a gas boiler is included.

Natural gas prices are extracted from the Eurostat 2022 actualized data on natural gas prices referring to the 2nd half of 2021 [25]. Prices on natural gas are provided per each country, for a kilowatt-hour (kWh) unit annually, for European currency (€) (Table 30: Natural gas prices for 2021 of the countries taken into account for the pilots).

Table 30: Natural gas prices for 2021 of the countries taken into account for the pilots

GEO (Labels)	Natural gas price – 2021 (€/kWh)
Denmark	0,1247
Greece	0,1014

The economic assessment results of the conventional solutions are depicted in the following diagrams.

Figure 35: Economic assessment results for the technology systems considered in Greek-pilot in the example of a residential building

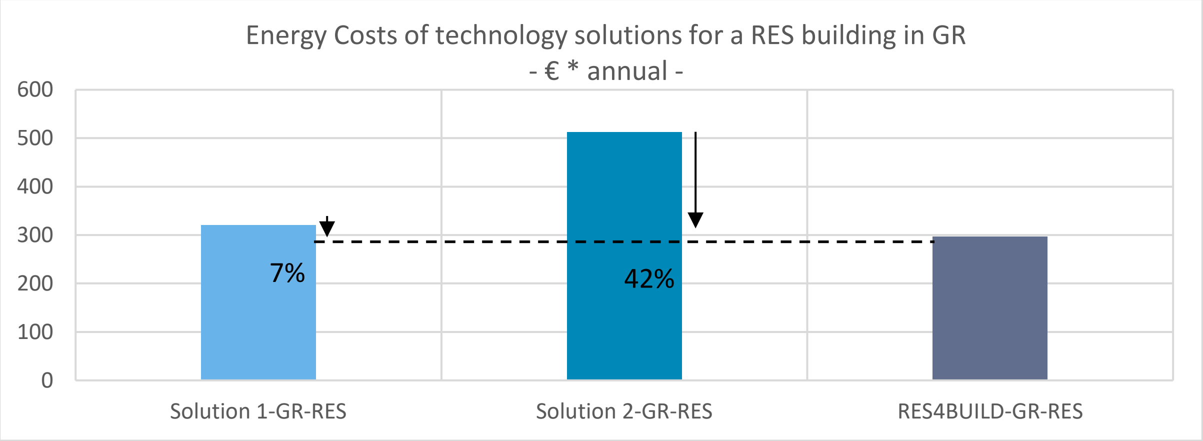
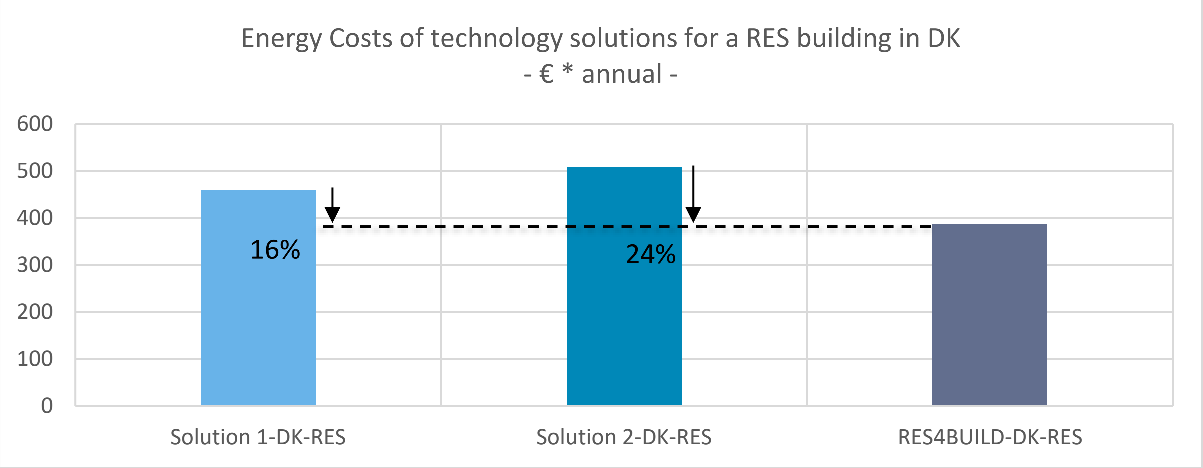


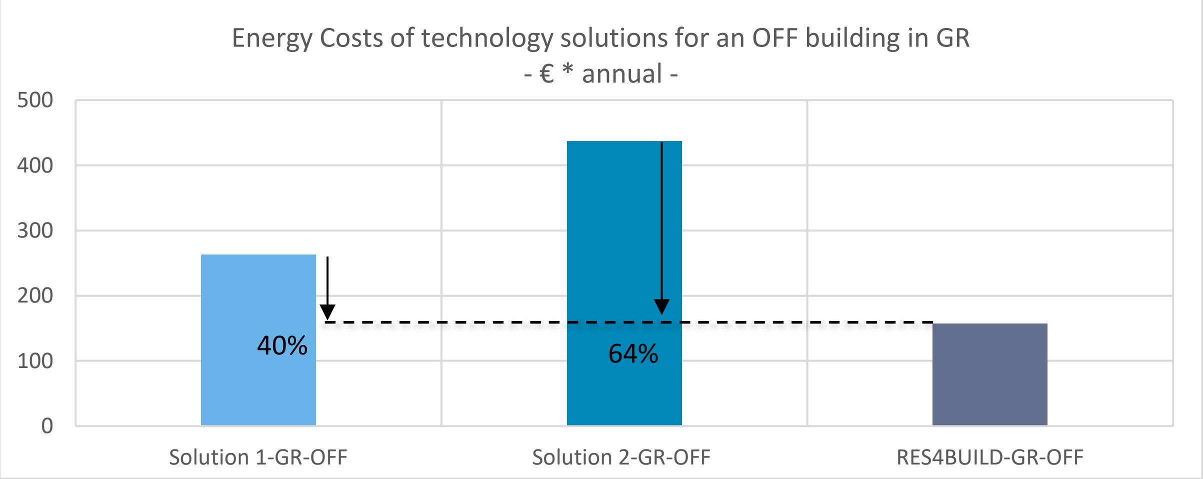
Figure 35: Economic assessment results for the technology systems considered in Greek-pilot in the example of a residential building shows the costs of conventional technology solutions 1 and 2 in a residential building, for the electricity consumed from the Greek electricity grid. Solution 2 which considers a gas boiler and an AC device requires electricity from the grid amounting to 512,9 € annually, while Solution 1 which foresees the application of an air-source heat pump requires electricity from grid at the cost of 320,2 € annually. The RES4BUILD system would have an expenditure of 296,6 € annually for a residential energy demand under the Greek electricity grid supply. This indicates the potentials of costs reduction through the RES4BUILD system with around 7% in comparison to Solution 1 and with up to 42% compared to Solution 2.

Figure 36: Economic assessment results for the technology systems considered in Danish-pilot in the example of a residential building



In Figure 36 the costs of energy consumed from the Danish electricity grid for a residential use type are depicted for Solutions 1 and 2 of conventional technologies and compared to the RES4BUILD system. Solution 2 (gas boiler & AC) acquires energy from the grid at costs of 508,3 € annually, and Solution 1 (air-source heat pump) has an electricity demand from the grid amounting at 460,0 € annually. The annual costs of the RES4BUILD system for electricity consumed from the grid amount to 387,0 € annually, depicting potentials of cost reduction with 16% in relation to Solution 1 and of 24% compared to Solution 2.

Figure 37: Economic assessment results for the technology systems considered in Greek-pilot in the example of an office building



In Figure 37: Economic assessment results for the technology systems considered in Greek-pilot in the example of an office building are shown the electricity consumption costs of technology solutions for an office building under the Greek electricity grid supply. Solution 2 (gas boiler & AC) has an electricity demand from the grid which amounts to 437,3 € annually, while Solution 1 (air-source heat pump) acquires electricity from the grid at the costs of 262,8 € annually. The RES4BUILD system costs for the electricity required from the grid mix, are significantly lower in comparison to the two conventional solutions. The costs for RES4BUILD integrated system amount to 157,4 €, presenting a potential for costs reduction of 40% in comparison to Solution 1 and of 64% in comparison to Solution 2.

Figure 38: Economic assessment results for the technology systems considered in Danish-pilot in the example of an office building

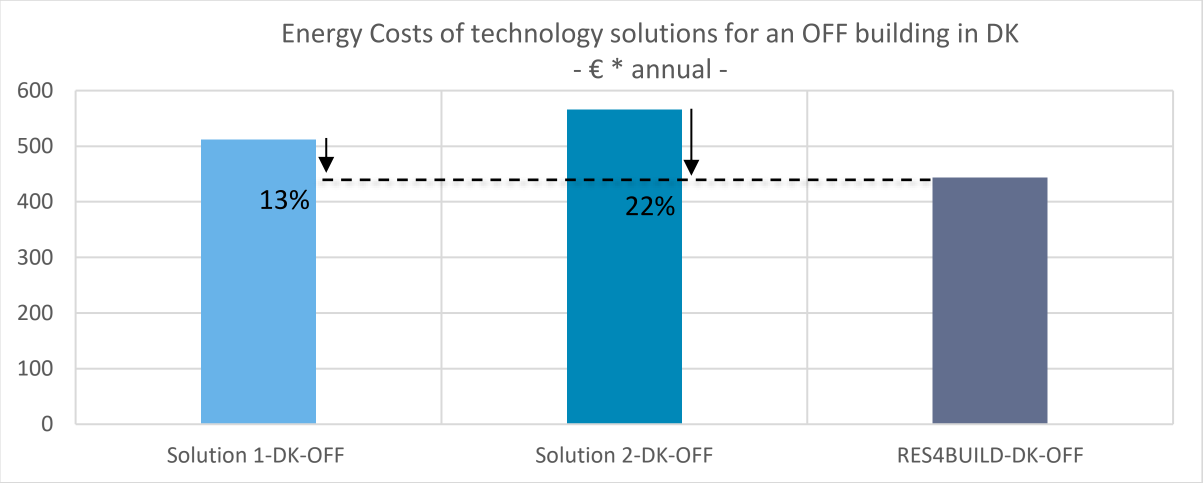


Figure 38: Economic assessment results for the technology systems considered in Danish-pilot in the example of an office building shows the economic assessment results of the technology solutions in the case of an office type of use, consuming electricity from the Danish grid conditions. Similar to the previous cases, Solution 2 (gas boiler & AC) accounts for the highest costs for electricity consumption which amount to 566,1 € annually. Solution 1 (air-source heat pump) on the other hand, consumes less electricity from the grid than Solution 2, amounting to 512,2 €, nevertheless higher than the cost expenditure from the RES4BUILD system. The costs for electricity consumption of the RES4BUILD system amount up to 444,0 € annually, indicating potential of cost reduction with 13% compared to Solution 1 and cost reduction up to 22% compared to Solution 2.

Results interpretation and Outlook

This study presents outcomes from LCA and LCE analyses carried out on the investigated technologies and the integrated technology systems for energy production in buildings, within RES4BUILD. The results of both analyses demonstrate that environmental impacts can be mitigated by optimization of material composition and choosing specific (and not generic) end-of-life scenarios of technologies if considered as standalone products. On the other hand the implementation of the RES4BUILD integrated energy generation system in buildings, leads to significant environmental and economic improvements, compared to conventional technology solutions.

In general, the outcomes of the technology assessment prove that LCA results are dependent on the material share in the single technologies, and can show where do the highest benefits in respect to climate change mitigation come from, e.g.: through considering alternative materials which are less impactful throughout the production stage, or through applying recycling and re-use scenarios during the end-of-life of metallic components. Taking into account that the incineration scenario for plastic and wooden elements enables the gain of credits in electricity and thermal energy, is of important consideration in the case of the building context and its operational phase assessment.

Specific conclusions and recommendations on the technologies LCA and LCE can be summarized as follows:

- The Double Mareco photovoltaic-thermal collector (DM-PVT) is a prototype technology developed within the context of RES4BUILD project. It is currently investigated for optimization of performance and efficient applicability for the project’s objectives. Therefore, a comparison analysis with similar PV or PVT market available existing technologies, cannot be directly carried out without consideration of the boundary conditions defined for the LCA in this report. The life cycle economics (LCE) assessment can only be carried out using average and statistical data, implying that no market price can be currently delivered for this innovative technology.
  LCA results provide important indications for the technology’s optimization potential in regards to environmental impact:
  The production of solar cells as part of the PVT receiver assembly contribute significantly to GWP. Since the application of such materials cannot be compromised due to their functional importance, it is then relevant to consider End-of-Life scenarios which can compensate for the high impact coming from their production.

- The magnetocaloric heat pump (MCHP) is a prototype technology investigated in RES4BUILD, and is currently being developed as a proof of concept within the project’s objectives. The Bill of Materials (BoM) represents under this context no optimized technology for mass and/or market production. The life cycle assessment (LCA) leads to high environmental impacts for the technology’s life span, which is to be expected since the developers’ focus lies currently on the optimization of performance (energy yield) and technical functions. In such a setting, the life cycle economics (LCE) assessment can only be carried out using average and statistical data, which means that no market price can be currently delivered for this innovative technology.
  LCA results provide important indications for the technology’s optimization potential in regards to environmental impact:
  Considerable use of metals other than the magnets (such as: cast iron, aluminium and steel) contribute significantly to GWP. Positive impact can be achieved through reduction of metals mass (weight) in the overall material composition. Considering reuse for the End-of-Life of magnets has a positive contribution to environmental impact. Nevertheless this does not imply that such a scenario is performed in practically every case, since it depends on the user’s decisions and the design of the technology. Continuous contact with the user and informative discussion regarding the importance of sending the magnets back to producer/ developer for reuse, and not just choosing the landfill route, can compensate significantly for the negative environmental

impacts caused during the magnets production. As mentioned, the technology is still a prototype, thus the LCA results are not recommended to be applied or used for comparison purposes.

- The vapour compression heat pump (VCHP) is a conventional technology investigated in RES4BUILD, for highest performance and efficient applicability in the context of the RES4BUILD integrated system for adaptability with the innovative technologies (PVT and MCHP) following the project's objectives. Under this condition the life cycle economics (LCE) assessment can only be carried out using average and statistical data, implying that no market price can be currently delivered for this technology under development.
  LCA results provide important indications for the technology's optimization potential in regards to environmental impact:
  Metals used for heat exchange (steel, copper and bronze), contribute significantly to GWP through their production stage, more so due to the high material share in the technology. Since the application of such materials cannot be compromised due to their functional importance, it is then relevant to consider End-of-Life scenarios which can compensate for the high impact coming from their production. Recyclability and reuse of these materials can lead to lower environmental impacts. Since the technology is still under development, LCA results are not recommended to be applied or used for comparison purposes unless same settings (performance and instalment location) are applied.

The economic assessment of the integrated systems is based on the available energy/ electricity consumption data provided from the simulation process run on the pilots, and does not take into account energy and cost credits gained by the RES4BUILD system for returning energy/ electricity in the grid, in case of surplus quantities produced. The consideration of energy sent back to the grid from the RES4BUILD integrated system would as a result lead to higher environmental and cost benefits.

Specific conclusions and recommendations on the technologies LCA and LCE can be summarized as follows:

- The LCA of the RES4BUILD integrated systems in two pilots (Greece and Denmark) for two building use types (residential and office) demonstrates that environmental impacts during the operational phase can be achieved by substituting conventional technology solutions of energy production in building with the RES4BUILD system:
  - By replacing a gas boiler and AC device with the RES4BUILD system in a residential building in Greece, up to 24% less GWP impact and up to 42% less costs can be achieved.
  - Replacing an air-source heat pump with the RES4BUILD system in a residential building in Greece, leads to 7% less GWP and 7% reduction of costs.
  - The replacement of a gas boiler and AC device by the RES4BUILD system in an office building in Greece, allows for a reduction of GWP with up to 51% reduction of costs with 64%.
  - Replacing an air-source heat pump with the RES4BUILD system in an office building in Greece, leads to 40% less GWP and 40% reduction of costs.
  - The replacement of a gas boiler and AC device by the RES4BUILD system in a residential building in Denmark, allows for a reduction of GWP with up to 69% and reduction of costs with 24%.
  - Replacing an air-source heat pump with the RES4BUILD system in a residential building in Denmark, leads to 16% less GWP and 16% reduction of costs.

- The replacement of a gas boiler and AC device by the RES4BUILD system in an office building in Denmark, allows for a reduction of GWP with up to 68% and reduction of costs with 22%.
- Replacing an air-source heat pump with the RES4BUILD system in an office building in Denmark, leads to 13% less GWP and 13% reduction of costs.

Generally, the carbon intensity of the national energy production has an impact on the potential environmental and costs reduction of the RES4BUILD system. In our study higher environmental and economic benefits of the RES4BUILD integrated system compared to two conventional systems, are found for the Danish electricity grid in the case of the residential type of use. Whereas for the office type of use, higher impact reduction potential is found in the Greek electricity grid. When comparing environmental and economic benefits regarding the replacement of the two conventional solutions with the RES4BUILD system in all cases, higher reduction potential come from substituting a condensing boiler combined with an AC, due to consideration of environmental impact and costs of national gas profiles in the Greek and Danish context.

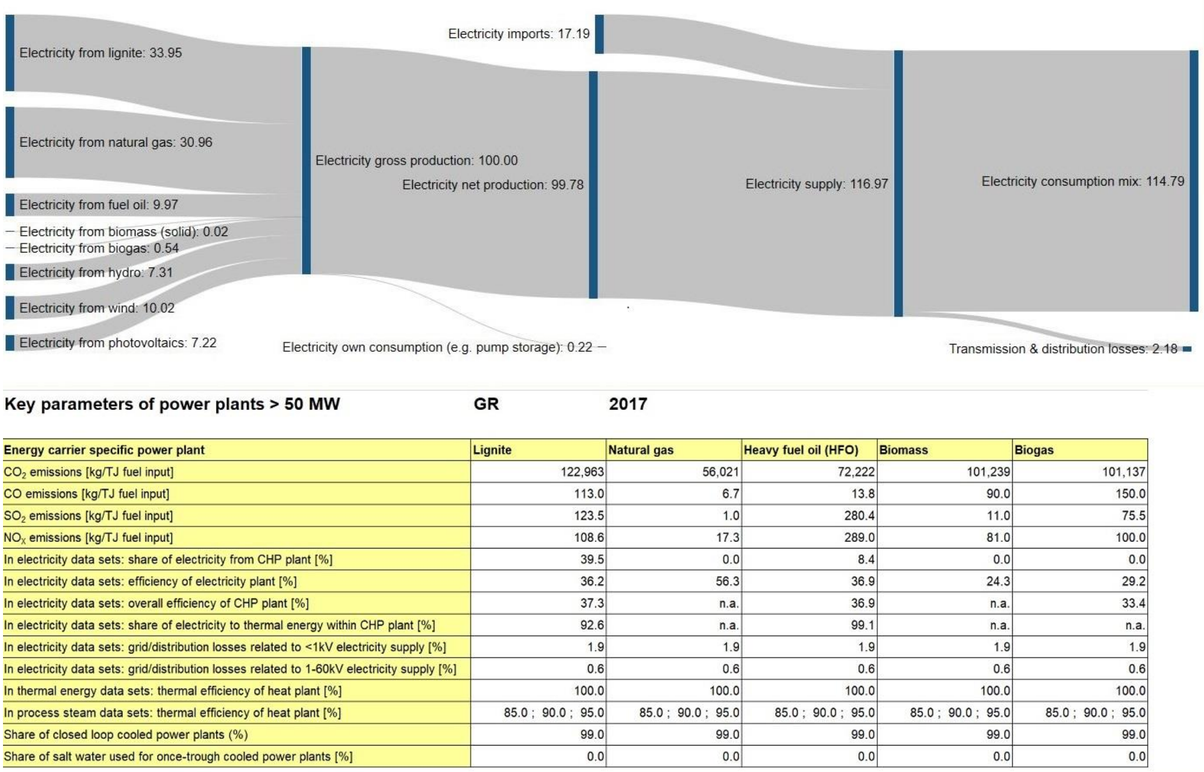
The consideration of annual input data for the integrated systems, leads to the analysis of the electricity impact from static annual consumption, and the reduction potentials are therefore provided statically. A dynamic consideration of the electricity changes in the building's life span should provide life cycle benefits of the system in time. Also, carrying out an analysis with variable electricity mix, according to EU future scenarios would provide environmental and cost credits of the expected electricity production improvements.

Different implementation strategies of the RES4BUILD system and solutions to different building use types can be further research and addressed on the higher building level. A study considering building structure (envelope) as well as integrated systems combined, should derive environmental and economic assessment values holistically and provide optimization solutions for the technologies throughout the building's lifespan.

List of figures

Annex I – Energy supply in the electricity grid mix of GR and DK

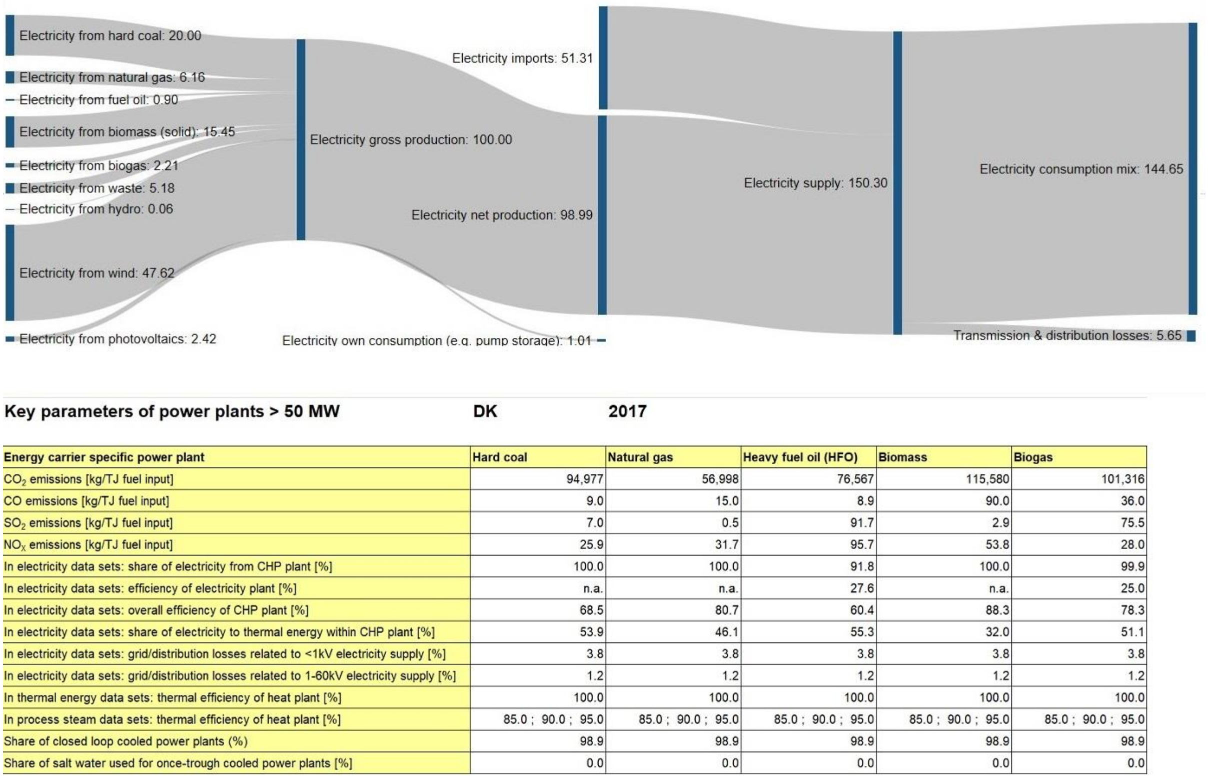
Figure 39: Electricity supply and key parameters of power plants in Greece (2017) [22]



Key parameters of power plants > 50 MW **GR** **2017**

Energy carrier specific power plant	Lignite	Natural gas	Heavy fuel oil (HFO)	Biomass	Biogas
CO_2 emissions [kg/TJ fuel input]	122,963	56,021	72,222	101,239	101,137
CO emissions [kg/TJ fuel input]	113.0	6.7	13.8	90.0	150.0
SO_2 emissions [kg/TJ fuel input]	123.5	1.0	280.4	11.0	75.5
NO_X emissions [kg/TJ fuel input]	108.6	17.3	289.0	81.0	100.0
In electricity data sets: share of electricity from CHP plant [%]	39.5	0.0	8.4	0.0	0.0
In electricity data sets: efficiency of electricity plant [%]	36.2	56.3	36.9	24.3	29.2
In electricity data sets: overall efficiency of CHP plant [%]	37.3	n.a.	36.9	n.a.	33.4
In electricity data sets: share of electricity to thermal energy within CHP plant [%]	92.6	n.a.	99.1	n.a.	n.a.
In electricity data sets: grid/distribution losses related to <1kV electricity supply [%]	1.9	1.9	1.9	1.9	1.9
In electricity data sets: grid/distribution losses related to 1-60kV electricity supply [%]	0.6	0.6	0.6	0.6	0.6
In thermal energy data sets: thermal efficiency of heat plant [%]	100.0	100.0	100.0	100.0	100.0
In process steam data sets: thermal efficiency of heat plant [%]	85.0 ; 90.0 ; 95.0	85.0 ; 90.0 ; 95.0	85.0 ; 90.0 ; 95.0	85.0 ; 90.0 ; 95.0	85.0 ; 90.0 ; 95.0
Share of closed loop cooled power plants (%)	99.0	99.0	99.0	99.0	99.0
Share of salt water used for once-trough cooled power plants [%]	0.0	0.0	0.0	0.0	0.0

Figure 40: Electricity supply and key parameters of power plants in Denmark (2017) [22]



Key parameters of power plants > 50 MW **DK** **2017**

Energy carrier specific power plant	Hard coal	Natural gas	Heavy fuel oil (HFO)	Biomass	Biogas
CO_2 emissions [kg/TJ fuel input]	94,977	56,998	76,567	115,580	101,316
CO emissions [kg/TJ fuel input]	9.0	15.0	8.9	90.0	36.0
SO_2 emissions [kg/TJ fuel input]	7.0	0.5	91.7	2.9	75.5
NO_X emissions [kg/TJ fuel input]	25.9	31.7	95.7	53.8	28.0
In electricity data sets: share of electricity from CHP plant [%]	100.0	100.0	91.8	100.0	99.9
In electricity data sets: efficiency of electricity plant [%]	n.a.	n.a.	27.6	n.a.	25.0
In electricity data sets: overall efficiency of CHP plant [%]	68.5	80.7	60.4	88.3	78.3
In electricity data sets: share of electricity to thermal energy within CHP plant [%]	53.9	46.1	55.3	32.0	51.1
In electricity data sets: grid/distribution losses related to <1kV electricity supply [%]	3.8	3.8	3.8	3.8	3.8
In electricity data sets: grid/distribution losses related to 1-60kV electricity supply [%]	1.2	1.2	1.2	1.2	1.2
In thermal energy data sets: thermal efficiency of heat plant [%]	100.0	100.0	100.0	100.0	100.0
In process steam data sets: thermal efficiency of heat plant [%]	85.0 ; 90.0 ; 95.0	85.0 ; 90.0 ; 95.0	85.0 ; 90.0 ; 95.0	85.0 ; 90.0 ; 95.0	85.0 ; 90.0 ; 95.0
Share of closed loop cooled power plants (%)	98.9	98.9	98.9	98.9	98.9
Share of salt water used for once-trough cooled power plants [%]	0.0	0.0	0.0	0.0	0.0

Annex II – LCIA results of technologies

Figure 41: LCIA results for the production (A1-A3) and end-of-life (C+D) of the PVT collector, the MCHP and the VCHP expressed in environmental indicators as defined on page 24 (based on EN 15804 + A1).

	PVT collector			MCHP			VCHP		
Indicators	**Production**	**End of life**	**Life cycle**	**Production**	**End of life**	**Life cycle**	**Production**	**End of life**	**Life cycle**
Ozone Depletion Potential (ODP) [kg R11 eq.]	7,2019E-09	1,77647E-08	2,49666E-08	9,0638E-08	1,5382E-10	9,07918E-08	8,45111E-07	6,47323E-08	9,09843E-07
Acidification potential (AP) [kg SO2 eq.]	1,493886261	-0,325901444	1,167984817	16,00308507	-11,2853231	4,717761976	2,596595868	-1,367552842	1,229043026
Eutrophication potential (EP) [kg Phosphate eq.]	0,163256373	-0,017451105	0,145805268	0,997984199	-0,58956727	0,40841693	0,254239487	-0,031390915	0,222848572
Photochemical Ozone Creation Potential (POCP) [kg Ethene eq.]	0,072025539	-0,014086257	0,057939282	1,242407599	-0,78570297	0,456704625	0,150828216	-0,068314888	0,082513328
Abiotic depletion potential for non fossil resources (ADPE) [kg Sb eq.]	0,001329421	-0,00052646	0,000802961	0,016512217	-0,00401967	0,012492546	0,058243756	-0,059239112	-0,000995356
Abiotic depletion potential for fossil resources (ADPF) [MJ]	4684,35317	-815,7461463	3868,607024	42199,08961	-21118,5014	21080,58817	4388,074826	-1327,415803	3060,659023
Total use of renewable primary energy resources (PERT) [MJ]	1443,152033	-457,580293	985,5717404	19297,18584	-12862,6239	6434,561971	1813,721796	-396,7996408	1416,922155
Total use of non-renewable primary energy resources (PENRT) [MJ]	5264,096317	-992,5149038	4271,581414	47717,50035	-23075,1104	24642,38994	6378,603224	-1401,080374	4977,52285

Annex III – LCIA results of integrated systems

Figure 42: LCIA results for the operational phase (B6) of the RES4BUILD integrated system in four case studies, expressed in environmental indicators as defined on page 28 (based on EN 15804 + A1).

Indicators	RES – GR	OFF – GR	RES – DK	OFF – DK
Ozone Depletion Potential (ODP) [kg R11 eq.]	2,43881E-11	1,29437E-11	1,19828E-11	1,3749E-11
Acidification potential (AP) [kg SO2 eq.]	3,156102415	1,675066039	0,364861723	0,418642243
Eutrophication potential (EP) [kg Phosphate eq.]	0,200616546	0,106474987	0,077577752	0,089012691
Photochemical Ozone Creation Potential (POCP) [kg Ethene eq.]	0,201521613	0,106955341	0,03738479	0,042895297
Abiotic depletion potential for non fossil resources (ADPE) [kg Sb eq.]	0,000203232	0,000107863	0,000138653	0,00015909
Abiotic depletion potential for fossil resources (ADPF) [MJ]	11552,1007	6131,148176	2574,273879	2953,72116
Total use of renewable primary energy resources (PERT) [MJ]	4447,408458	2360,412271	6700,430318	7688,071954
Total use of non-renewable primary energy resources (PENRT) [MJ]	11875,68967	6302,8894	3325,619021	3815,814374

References

1. IEA EBC || Annex 72 || Assessing Life Cycle Related Environmental Impacts Caused by Buildings || IEA EBC || Annex 72. Available online: https://annex72.iea-ebc.org/ (accessed on 3 June 2021).
2. Röck, M.; Saade, M.R.M.; Balouktsi, M.; Rasmussen, F.N.; Birgisdottir, H.; Frischknecht, R.; Habert, G.; Lützkendorf, T.; Passer, A. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Applied Energy 2020, 258, 114107, doi:10.1016/j.apenergy.2019.114107.
3. Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca. Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. Global Warming of 1.5°C An IPCC Special Report on the impacts of global warming of 1.5°C above.
4. European Commission. The International reference Life Cycle Data System - ILCD Handbook: Towards more sustainaible production and consumption for a ressource-efficient Europe.
5. Gantner, J., et al. EeBGuide Guidance Document Part A: Products. Operational guidance for Life Cycle Assessment studies of the Energy-Efficient Buildings Initiative. 2011
6. Gantner, J. et al. EeBGuide Guidance Document Part B: Buildings. Operational guidance for Life Cycle Assessment studies of the Energy Efficient-Buildings Initiative. 2011
7. Deutsches Institut für Normung e.V. DIN EN 15804 2012 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products EN 15804:2012+A1:2013
8. Deutsches Institut für Normung e.V. DIN EN ISO 14040 Environmental management – Life Cycle Assessment – Principles and framework (ISO 14040:2006 + A1:2020)
9. Deutsches Institut für Normung e.V. DIN EN ISO 14044 2018 Environmental management – Life Cycle Assessment – Requirements and guidelines (ISO 14044:2006 + A 1:2018 + A2:2020)
10. Verein Deutscher Ingenieure VDI, Purchase, operating and maintenance of production equipment using Life Cycle Costing (LCC) VDI 2884. 2005
11. International Standard ISO 15686-5 Buildings and constructed assets – Service life planning – Part 5: Life-cycle costing. 2017
12. Deutsches Institut für Normung e.V. DIN EN 16627 Sustainability of construction works – Assessment of economic performance of buildings – Calculation methods. EN 16627:2015
13. Deutsches Institut für Normung e.V. DIN EN 15643-5 Sustainability of construction works – Sustainability Assessment of buildings and civil engineering works – Part 5: Framework on specific principles and requirement for civil engineering works. EN 15643-5:2017
14. Deutsches Institut für Normung e.V. DIN EN 15978 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method. EN 15978:2011
15. BlueMouse GmbH. ecoinvent. Available online: https://www.ecoinvent.org/ (accessed on 20 July 2021).
16. Thinkstep GaBi. Available online: https://gabi.sphera.com/international/support/gabi-version-history/gabi-ts-version-history/
17. Ecobilane PwC. DEAM – Data for Environmental Analsys and Management. www.ecobilan.com/uk_deam01_02.php
18. U.S. Life Cycle Inventory Database. Available online: https://www.nrel.gov/lci/ (accessed on 20 July 2021).

19. Lasvaux, S.; Habert, G.; Peuportier, B.; Chevalier, J. Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. *Int J Life Cycle Assess* **2015**, *20*, 1473–1490, doi:10.1007/s11367-015-0938-z.
20. Institut für Bauen und Umwelt. Product Category Rules for Building-Related Products and Services. Available online: https://ibu-epd.com/.
21. Product Category Rules PCR 2020 Electricity, Steam and Hot Water Generation and Distribution, Product Category Classification: UN CPC 171, 173 2007:08 Version 4.0
22. GaBi Software System and Database for Life Cycle Engineering 1992-2021 © Sphera Solutions GmbH Version 10.5.0.78. Schema 8007.
23. MG Sustainable Engineering, http://mgsustainable.com/#top
24. Eurostat 2022. Electricity prices by type of user. Last updated on 29/04/2022. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics
25. Eurostat 2022. Natural gas price statistics. Natural gas prices (including taxes) for household consumers, second half 2021. Last updated on 29/04/2022. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics