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Definition of environmental criteria for rating heating, ventilation, and air conditioning systems based on the LCA method

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From the beginning to the eternity, a dedication to the greatest event of my life.

Thanks to his honesty & friendship.

Abstract – EN

In buildings, energy consumption and carbon dioxide production are two major problems. The principal energy consumers in buildings are heating, ventilation, and air conditioning systems, which have not been thoroughly investigated with a life cycle assessment approach. By using life cycle assessment methods, the research compares two distinct heating, ventilation, and air conditioning systems in terms of their environmental impacts. The target group could be the energy systems which will be installed in mega event organizations like Milano Cortina 2026 or other temporary buildings which will be placed in Milano, Italy. The different heating, ventilation, and air conditioning system types being analyzed include electric heat pump and natural gas boiler. According to the reported energy need for the new buildings in Italy, for both systems, it is considered equal to 89.1 [kWh /m^2 /y] and as a hypothesis the area is 150 [m^2]. The environmental footprints are analyzed using the environmental life cycle assessment method. The life cycle assessment was conducted in accordance with ISO 14040-44 and EN 15804 standards. It was performed using SimaPro software with the ecoinvent v3 database. The life cycle impact assessment method used was EN 15804 + A2 Method V1.03 / EF 3.0; utilized to determine the characterization, normalization, and weighting procedures. The purpose and scope of the life cycle assessment, the life cycle inventory, the life cycle impact analysis, and interpretation are all fully described in this study. Since the weight of two impact categories of “climate change” and “Resource use, minerals, and metals” prevailed over the rest of the categories, the focus of this research put on these two impact categories. Findings demonstrate that the usage phase of natural gas boiler with the ratio of 77% and the end-of-life stage of electric heat pump with a ratio of 51% under the impact category of climate change and components with ratios of 55% and 99% for electric heat pump and natural gas boiler respectively, under the impact category of resource use mineral and metals, have the significant influence on the environment. The variables impacting these effect categories were identified with a deeper investigation. In conclusion, the rating system is proposed to reduce CO_2eq emissions and the depletion of natural non-fossil resources in heating, ventilation, and air conditioning systems with temporary operation. This rating system introduces the criteria to manage the refrigerant, wastes and energy, that have a high potential for controlling the environmental impact and strategies for converting existing systems to eco-friendly ones. According to the results of the life cycle assessment and considering the green rating building systems, the points are assigned for each of the criteria set. Another useful technique for simplifying the evaluation of these systems is rating.

Key words: LCA, Environmental impact, Temporary building, HVAC, Rating system, Italy.

Abstract – IT

Negli edifici, il consumo di energia e la produzione di anidride carbonica sono due grandi problemi. I principali consumatori di energia negli edifici sono i sistemi di riscaldamento, ventilazione e condizionamento dell'aria, che non sono stati studiati a fondo con un approccio di valutazione del ciclo di vita. Lo scopo di questa ricerca è confrontare gli impatti ambientali di due distinti sistemi di riscaldamento, ventilazione e condizionamento dell'aria con un approccio di valutazione del ciclo di vita. Il gruppo target potrebbe essere costituito dai sistemi di riscaldamento, ventilazione e condizionamento dell'aria che saranno installati in organizzazioni di mega eventi come Milano Cortina 2026 o altri edifici temporanei che saranno collocati a Milano, in Italia. Le diverse tipologie di impianto di riscaldamento, ventilazione e condizionamento oggetto di analisi comprendono la pompa di calore elettrica e la caldaia a gas naturale. Secondo il fabbisogno energetico riportato per i nuovi edifici in Italia, per entrambi gli impianti, è considerato pari a 89.1 [kWh /m^2 /a] e come ipotesi l'area è di 150 [m^2]. Le impronte ambientali vengono analizzate utilizzando il metodo di valutazione del ciclo di vita ambientale. La valutazione del ciclo di vita è stata condotta in conformità agli standard ISO 14040-44 e EN 15804. È stato eseguito utilizzando il software SimaPro con il database ecoinvent v3. Il metodo di valutazione dell'impatto del ciclo di vita utilizzato è stato EN 15804 + Metodo A2 V1.03 / EF 3.0; utilizzato per determinare le procedure di caratterizzazione, normalizzazione e ponderazione. Lo scopo e l'ambito della valutazione del ciclo di vita, dell'inventario del ciclo di vita, dell'analisi dell'impatto del ciclo di vita e dell'interpretazione sono tutti ampiamente descritti in questo studio. Poiché il peso di due categorie di impatto "cambiamento climatico" e "Uso delle risorse, minerali e metalli" ha prevalso sul resto delle categorie, l'attenzione di questa ricerca si è concentrata su queste due categorie di impatto. I risultati dimostrano che la fase di utilizzo della caldaia a gas naturale con un rapporto del 77% e la fase di fine vita della pompa di calore elettrica con un rapporto del 51% nella categoria di impatto del cambiamento climatico e dei componenti con rapporti del 55% e 99 % rispettivamente per la pompa di calore elettrica e la caldaia a gas naturale, nella categoria di impatto dell'uso delle risorse minerali e metalli, hanno un'influenza significativa sull'ambiente. Le variabili che influenzano queste categorie di effetti sono state identificate con un'indagine più approfondita. In conclusione, il sistema di rating è proposto per ridurre le emissioni di CO_2eq e l'esaurimento delle risorse naturali non fossili negli impianti di riscaldamento, ventilazione e condizionamento con funzionamento temporaneo. Questo sistema di rating introduce i criteri per la gestione del refrigerante, dei rifiuti e dell'energia, che hanno un alto potenziale per il controllo dell'impatto ambientale e le strategie per convertire i sistemi esistenti in quelli ecologici. In base ai risultati della valutazione del ciclo di vita e considerando i sistemi di green rating degli edifici, vengono assegnati i punti per ciascuno dei criteri stabiliti. Un'altra tecnica utile per semplificare la valutazione di questi sistemi è il rating.

Key words: LCA, Environmental impact, Temporary building, HVAC, Rating system, Italy.

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Abbreviations

HVAC	Heating, Ventilation, Air Conditioning
BES	Building Energy System
GHG	Green House Gas
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
GBRS	Green Building Rating System
NGB	Natural Gas Boiler
EHP	Electric Heat Pump
SC	Scenario
LS	Life span
CC	Climate Change
OD	Ozone Depletion
IR	Ionizing Radiation
POF	Photochemical Ozone Formation
PM	Particulate Matter
HTNC	Human Toxicity, Non-Cancer
HTC	Human Toxicity, Cancer
A	Acidification
EF	Eutrophication, Freshwater
EM	Eutrophication, Marine
ET	Eutrophication, Terrestrial
EFW	Ecotoxicity, Freshwater
LU	Land Use
WU	Water Use
RUF	Resource Use, Fossils
RUMM	Resource Use, Minerals, and Metals
Comp.	Components
Mfp.	Manufacturing Process
Dist.	Distribution
Pack.	Packaging
Use.	Use Phase
Main.	Maintenance
EOL	End Of Life
CO_2 eq	Carbon Dioxide equivalent

1 Introduction

Researchers deal with two major problems: energy consumption and carbon dioxide production in buildings [1]. Statistics show that by 2020, the share of buildings will reach 35–40% in energy consumption and CO_2 production [2]. This has led to lots of challenges regarding supplies of energy, energy resources quick depletion, increase in building service demands, improvised comfort lifestyle along with time increase spend in builds; this all has increased the energy consumption [3]. If the first problem is solved, the next problem will be solved as well. Because the production of carbon dioxide is due to energy consumption in different parts of the building.

The global and European strategies have focused on reducing the operational Green House Gas (GHG) emissions through measures such as efficient building technologies and replacing fossil fuel-based energy carriers with renewable sources [4].
The major areas of energy consumption in buildings are heating, ventilation and air conditioning systems, hot water, and lighting as well as the embodied energy of construction materials [5]. Therefore, to reduce energy consumption and environmental emissions, the mitigation strategy shall be focused on building energy services.

Moreover, in the last decade, the demand for temporary structures is expanding because of the growing of world events, artistic and sport programs, festival, fairs, etc. [6]. These buildings had to respond to sustainable design rules in term of flexibility, speed of execution with low budge, satisfy thermal, acoustic, and other performances to guarantee high level of climate comfort. Temporary buildings are exempted from the application of the minimum requirements to reduce energy in use as set by the European directive 2010/31/EU [7]due to their short-expected service life. Hence, it becomes even more important to consider the impact of their embodied energy and the one of their ends of life [8].

Most studies examine the environmental impact of the structural elements and the building envelope. While, only a few studies focus on the impact of building services, including HVAC systems. One of the biggest challenges is that existing studies generally cannot perform a detailed assessment, mainly due to the lack of data and methods to estimate the embodied environmental impact, especially for HVAC components composed of various raw materials. Another issue is the allocation of end-of-life impacts and the management of such installed HVAC systems considering their short life span.

The purpose of this research is to compare the environmental impacts of two distinct Heating, Ventilation, Air Conditioning systems (HVAC) with a LCA approach. The target group could be the HVAC systems which will be installed in mega event organizations like Milano Cortina 2026 or other temporary buildings which will be placed in Milano, Italy. The different HVAC system types being analyzed include electric heat pump (EHP) and natural gas boiler (NGB). In this study, a hypothetical area is equal to 150 [m^2] and according to the reported energy requirement for new building in Italy, it is assumed that the energy need is equal to 89.1 [kWh / m^2 /y].

The environmental footprints are analyzed using the environmental life cycle assessment method. The life cycle assessment was conducted in accordance with ISO 14040-44 and EN 15804 standards [9]. It was performed using SimaPro software with the ecoinvent v3 database. The life cycle impact assessment method used was EN 15804 + A2 Method V1.03 / EF 3.0; utilized to determine the characterization, normalization, and weighting procedures. This report includes all the details on the life cycle assessment goal and scope, the life cycle inventory, the life cycle impact analysis, and interpretation. Furthermore, product/service systems have been widely promoted as a pathway for businesses to transition to a circular economy. HVAC systems due to their frequent usage in mega events and temporary occasion were the best candidate to investigate of this kind of business model.

In this research, due to compare of the environmental effects of the regular HVAC ownership business model to serve the whole twenty-year lifespan and the HVAC rental business model to service the usage of only two months (during the event), four scenarios (SC) are defined and analysis of those scenarios which are related to the case studies with two-month life span, in accordance with circular economy policies was done to compare the environmental effects of the two NGB and EHP systems. Based on these findings, the best scenario is known as the business model with the least detrimental environmental effects, and as a result, a system for scoring these systems has also been introduced (considering the green building rating systems, circular economy strategies and the results of LCA of this study).

In a final summary, the goal of this research is targeted to the:

- Reducing greenhouse gas emissions as the ultimate objective (A holistic environmental perspective).
- To provide several circular economy-based scenarios to find the HVAC business model with the least negative environmental impact.
- To establish the essential environmental criteria for energy systems based on LCA analysis for short-term operation.
- To propose a rating system for HVACs so that users can choose the best one for their needs. (Considering the adjustment of circular economy approaches and green building rating systems on the results of this study's LCA).

Two different HVAC systems (Electric heat pump and Natural gas boiler) were evaluated in four scenarios using environmental life cycle assessment. In the first scenario all the relevant phases of the lifecycle of two appliances were included, and the result of this scenario is considered for presenting the final rating system. The life cycle stages included in the LCA were production (stages A1-A3), Transportation to site (A4), use stage (B1, B2, B6), end of life stage (C1-C4).

The HVAC system with best environmental footprint in a short time, in addition to the sort of systems and energy sources also depends on the purchase policies. The analysis of comparison between environmental impact of four scenarios was accomplished for Climate change [kg CO_2eq] and Resource use, minerals, and metals [kg Sb eq]. According to the EN15804 (A1+A2), climate change with the unit [kgCO_2eq], is an indicator of potential global warming due to emissions of greenhouse gases to air and depletion of abiotic resources, minerals, and metals with the unit [kg Sb eq], is an indicator of the depletion of natural non-fossil resources [10].

The results show that the usage phase of NGB, the end of life for EHP, and the components for both systems account for most CO_2 eq contributions under the category of climate change. A detailed analysis of the results reveals that controlling the decrease of environmental consequences is greatly influenced by the management of emissions and wastes, materials, and energy.

It was made feasible for a rating system to be introduced by considering these findings and calculating the amount of each participant's contribution to total effort. The assumptions and scenarios put to the test in this LCA research formed the basis for the findings. Consequently, a few uncertainties might have an impact on the LCA results. To develop a dynamic and comprehensive system for all power generation systems, it is envisaged that future research would be able to broaden and test these scenarios across a variety of energy systems. The expansion of the range of case studies in more variety of circumstances, which is presently constrained by the availability of just two products, will provide the basis for future upgrades to this subject.

In order to validate the findings of the LCA evaluation of the broad range of products with various features and characteristics, other considerations beyond the environmental perspective, such as all circular economy strategies, might be included to the inquiry. The findings will be used to advise Italian LCA specialists and building energy service designers in the Lombardy province in making more environmentally friendly decisions for limited period performance energy systems.

Life cycle assessment of building energy systems has been considerably studied previously. However, to the best of the knowledge of the researcher, there has been less focus on the investigation of LCA of temporary buildings over a short period of time. In fact, in this research the aim is determination of the most significant environmental consequences of such case and consequently, proposing a rating system for HVAC systems based on circular economy approaches and green building rating systems. This would be the innovative aspect of this research.

2 Methodology

The comparison process for the building energy systems under evaluation is described in this chapter. The methods utilized to establish the system boundaries, the allocation and cut-off principles, the functional unit, the method for assessing the life cycle impacts, and the targeted application are all described in depth.

2.1 System boundary

The system boundary determines which unit processes shall be included within the LCA[11]. The boundary of the study is established by the building energy system using the stages of the construction works life cycle from EN 15804. This study considers the "cradle to grave" stages (A1-A3) to (C1-C4). While the installation stage (A5), the phases (B3, B4, B5, B7) and the deconstruction demolition phase (C1), were excluded, due to the uncertainty of the information, the high rate of variance from system to system, and the limited impact of these phases. Furthermore, secondary data from the ecoinvent v3 inventory database was applied to analyze each step. Building energy system life cycle stages included:

Product stage	A1: Components (row material supply and production) A2: Assembling (manufacturing with energy and water consumptions, welding, waste, transport of components to the manufacture plus packaging) A3: Manufacturing
	A4: Distribution (transport from manufacture to the consumer/site)
Use phase	B1: Use (electricity and natural gas consumption) B2: Maintenance (plus related necessary transport) B6: Operational energy use
	C2: Transport (from site to waste processing facilities) C3: Waste processing (for reuse, recovery/recycling) C4: Disposal

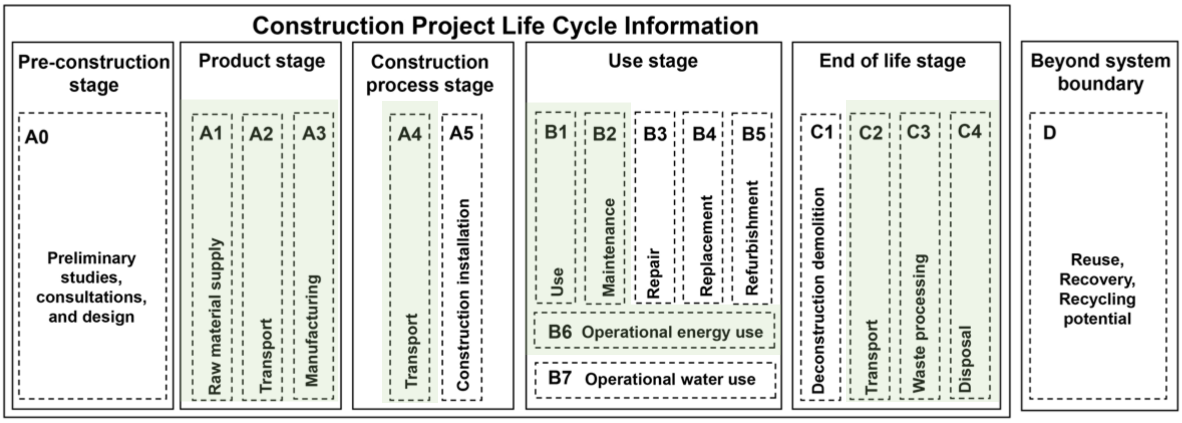


Figure 1- Life cycle stages for construction works [11].

2.2 Multifunctionalities and cut-off rules

The tool allows the management of the multifunctionality following the ecoinvent cut-off database concerning (i) component production, (ii) assembly, (iii) distribution, and iv) end of life phases. Specifically for the end-of-life phase, the idea behind the allocation rule adopted, called 100:0 or cut-off or recycled content is that the primary production of materials is always allocated to the primary user [*12*]. According to ISO 14044, the overall product system and the unit processes require three cutoff criteria including mass, energy, and environmental relevancy [12]. In this study, two types of allocation were employed.

1. The energy (electricity and heat) and water consumption for the manufactu1ring stage were distributed by mass. In particular, the reports by Jungbluth, N. [13] and Primas, A. [14], were utilized, which provided information per kilogram of product based on the annual usage of reference industries.
2. The cut-off approach suggested in the ecoinvent v3 database was applied to the end-of-life simulation [15].

Within the system boundaries, the cut-off rule for environmental impact was defined at 1%, which implied that inputs and outputs below this level were excluded from the LCA models. Seals, glues, transportation, and the delivery of packaging materials to manufacturing plants are a few examples. A compatible cut-off method known as "allocation, cut off, EN 15804" is included in more recent versions of the SimaPro software, although this version was not accessible under the Polimi license.

2.3 Functional unit

The functional unit (FU) is the quantified performance of a produced system used as a reference unit [16]. In this research, the functional unit was set as 1 kWh of thermal energy provided for space heating. The surface of the dwelling was established equal to 150 m^2 located in Italy, Milan which is considered in middle climate zone. Since the function is considered as a temporary building (placed in Olympic game event of Milano Cortina 2026), the lifespan is equal to two months.

2.4 Life cycle impacts assessment

An Environmental Life Cycle Assessment (E-LCA) was performed to accomplish the purpose behind this study. A life cycle assessment is a systematic, quantitative approach for analyzing the potential environmental impacts of products, services, and operations, according to EN ISO 14040. It incorporates life cycle conceptualizing, a way of thinking that considers every stage of a process, product, or service. Both ISO 14040 and ISO 14044 provide standard LCA guidelines [17]. Because life cycle evaluation is an iterative process where the outcomes of one stage have an impact on all subsequent phases, the arrows in the accompanying diagram are circular.

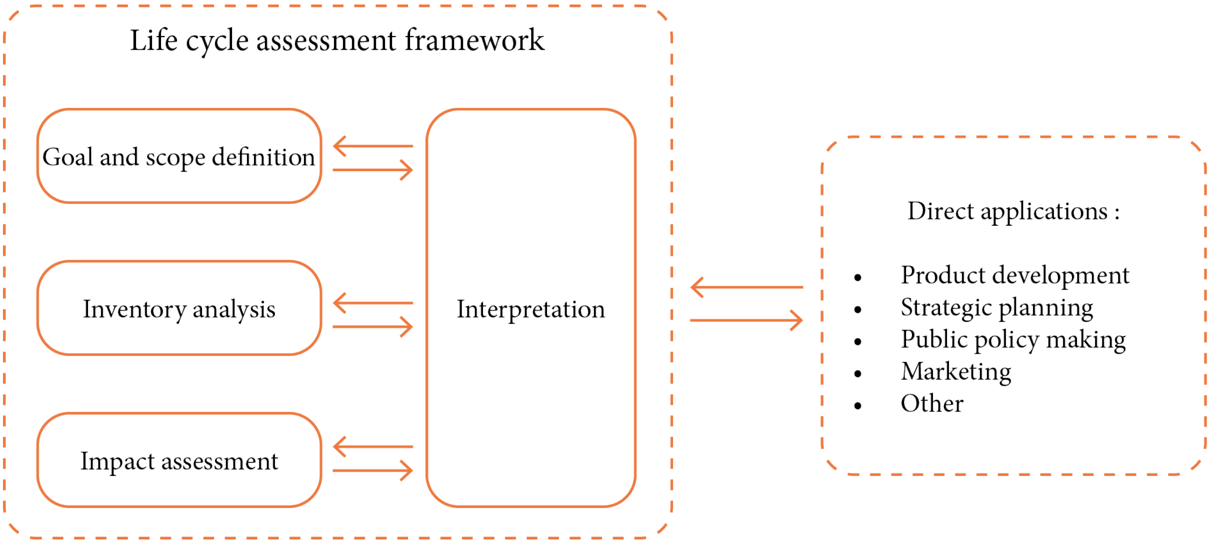


Figure 2- Components of a life cycle assessment (LCA) according to ISO [18].

The EN 15804[11]. lists nineteen categories required for the LCIA. Although, in this study the environmental profile of natural gas boiler and electric heat pump was expressed considering two impact categories, following the EN 15804 + A2 Method V1.03 / EF 3.0 normalization and weighting set.

1. Climate Change (CC) with a time horizon of 100 years
2. Resource Use, Mineral and Metals (RUMM).

3 Literature review

Building construction has an important role in sustainable development, which is not only due to participation in the national economy, but it is due to the constructed environment has a great influence on life quality, comfort, security, health, etc. Construction, maintenance and updating of the constructed environment have potential effects on the environment. buildings consume most of the unrecoverable resources and create a great amount of waste, and buildings create half of the total carbon dioxide. The current building construction challenge is creating economical buildings that increase life quality while reducing social, economic, and environmental effects. Achieving sustainability in buildings and construction is the goal emphasized more these days. There are many theoretical basics but some of them are not practical [19].

On the other hand, technology consciously focuses, directs, and transforms energy, matter, and information to improve the state of the planet. The main factor causing environmental deterioration is the increasing use of energy-rich fossil fuels. Energy sources have a direct impact on future ecological prospects since matter is energy embodied, and humankind's need for materials is at an all-time high. The necessity for industrial processes with substantial embodied energy makes the proposed solution move to 100% renewable power. Finding solutions for unexpected consequences at the core of environmental problems requires an understanding of abstract energy principles. Major environmental effects might be difficult to detect during complex details, making it simple for producers to externalize significant environmental effects or shift one ecological expense for another.

The sustainable transformation of the building sector is one of the biggest levers to achieve global climate protection agreements. Therefore, individual decisions regarding Building Energy Systems (BESs) become more important and building stakeholders require tangible options to create an energy-efficient and renewable-energy-based building stock [20]. This research aims to address this problem and presents a decision support system based on a software engineering and LCA approach that follows the guidelines of the design science research methodology and seeks to provide guidance for investment decisions in BESs by highlighting environmental impacts of energy systems in building.

This chapter provides brief introduction of primary definitions such as sustainability/sustainable buildings, Green Building Rating Systems (GBRs), Life Cycle Assessment (LCA) and Circular Economy (CE) in the built environment. Since this research deals with sustainability within the built environment and constructions, it is needed to define at the beginning some of the used definitions.

3.1 Sustainability

Sustainable construction is defined as "the creation and responsible management of a healthy built environment based on resource efficient and ecological principles". The OECD project has identified five objectives for sustainable buildings [21]:

- Resource Efficiency
- Energy Efficiency (including Greenhouse Gas Emissions Reduction)
- Pollution Prevention (including Indoor Air Quality and Noise Abatement)
- Harmonization with Environment (including Environmental Assessment)
- Integrated and Systemic Approaches (including Environmental Management System)

Sustainable building involves considering the whole life of buildings, taking environmental quality, functional quality, and future values into account. It is therefore the thoughtful integration of architecture with electrical, mechanical, and structural engineering resources [22]. Different climates make different demands on lighting, solar control, ventilation, and temperature control. Generally, in warm climates heat is rejected while light and air are admitted, provided the air can cool and the light is diffuse. In cool climates light and heat are retained while air is not required for cooling [23].
To sum up, in the following table, some selected definitions about sustainable construction and building are shown.

Sustainability	Definition
Sustainable Construction (SC) [24]	Sustainable construction refers to construction activities whose negative impacts are minimized, and positive impacts maximized to achieve a balance in terms of environmental, economic, and social performance.
Sustainable Construction (SC) [25]	A high-performance property that considers and reduces its impact on the environment and human health
Sustainable Construction (SC) [25]	Healthy facilities designed and built in a resource- efficient manner, using ecologically based principles
Sustainable Building [25]	"Sustainable building" can be defined as those buildings that have minimum adverse impacts on the built and natural environment, in terms of the buildings themselves, their immediate surroundings and the broader regional and global setting. "Sustainable building" may be defined as building practices, which strive for integral quality (including economic, social, and environmental performance) in a very broad way. Thus, the rational use of natural resources and appropriate management of the building stock will contribute to saving scarce resources, reducing energy consumption (energy conservation), and improving environmental quality.

Table 1- Definitions about sustainable construction and buildings [22].

Sustainable building principles

It is estimated that by 2056, global economic activity will have increased fivefold, global population will have increased by over 50%, global energy consumption will have increased nearly threefold, and global manufacturing activity will have increased at least threefold. Globally, the building sector is arguably one of the most resource-intensive industries. Compared with other industries, the building industry rapidly growing world energy use and the use of finite fossil fuel resources has already raised concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts ozone layer depletion, carbon dioxide emissions, global warming, climate change. Building material production consumes energy, the construction phase consumes energy, and operating a completed building consumes energy for heating, lighting, power, and ventilation. In addition to energy consumption, the building industry is considered as a major contributor to environmental pollution, a major consumption of raw materials, with 3 billion tons consume annually or 40% of global use and produces an enormous amount of waste [26].

The sustainable construction strategy is a means of communicating the industry's obligation to save the environment. The term "sustainable building" refers to a variety of practices used to carry out construction projects that cause less damage to the environment, such as preventing waste production, increasing the reuse of waste in the production of building materials, and managing waste while also being advantageous to society and financially profitable for the company. According to Hill and Bowen, environmentally friendly construction begins with the design stage of a project and continues throughout the building's life until it is eventually demolished, and the materials are recycled to reduce the waste stream associated with destruction. The authors then describe sustainable building as consisting of four principles: social, economic, biophysical, and technical. Amongst the published work relating to the principles of sustainable building are collated in the following table [27].

Authors	Proposed principles for sustainable building
Halliday [27]	***Economy:*** Good project management is a vital overarching aspect in delivering sustainable projects, both in the short and long term. ***Using Resources Effectively***: Buildings should not use a disproportionate number of resources, including money, energy, water, materials, and land during construction, use or disposal. ***Supporting Communities***: Projects should clearly identify and seek to meet the real needs, requirements and aspirations of communities and stakeholders while involving them in key decisions. ***Creating Healthy Environments***: Projects should enhance living, leisure, and work environments; and not endanger the health of the builders, users, or others, through exposure to pollutants or other toxic materials. ***Enhancing biodiversity***: Projects should not use materials from threatened species or environments and should seek to improve natural habitats where possible through appropriate planting and water use and avoidance of chemicals. ***Minimising pollution***: Projects should create minimum dependence on polluting materials, treatments, fuels, management practices, energy, and transport.
DETR [28]	Profitability and competitiveness, customers and client’s satisfaction and best value, respect and treat stakeholders fairly, enhance and protect the natural environment, and minimise impact on energy consumption and natural resources.

Hill and Bowen [29]	***Social pillar***: improve the quality of life, provision for social self-determination and cultural diversity, protect and promote human health through a healthy and safe working environment. ***Economic pillar***: ensure financial affordability, employment creation, adopt full cost accounting, enhance competitiveness, sustainable supply chain management. ***Biophysical pillar***: waste management, prudent use of the four generic construction resources (water, energy, material, and land), avoid environmental pollution etc. ***Technical pillar***: construct durable, functional, quality structure etc. These four principles are contained within a set of over-arching, process-oriented principles (e.g., prior impact assessment of activities).
Miyatake [30]	Minimization of resource consumption, maximization of resources reuse, use of renewable and recyclable resources, protection of the natural environment, create a healthy and non-toxic environment, and pursue quality in creating the built environment.
Cole and Larsson [31]	Reduction in resource consumption (energy, land, water, materials), environmental loadings (airborne emissions, solid waste, liquid waste) and improvement in indoor environmental quality (air, thermal, visual, and acoustic quality).
Kibert [32]	The creation and responsible management of a healthy built environment based on resource efficiency and ecological principles

Table 2- Principles of sustainable development [27].

There is a widely held opinion that the scope of sustainable building principles parallels those of sustainable development, which is all about the synergistic interactions between economic, social, and environmental sustainability. These three pillars (and the concepts that relate to them) are each supported by a group of process-focused principles, such as:

1. Conducting evaluations before to the beginning of proposed activities helps the decision-making process integrate data relevant to social, economic, ecological, and technical aspects.
2. The timeous involvement of key stakeholders in the decision-making process [33].
3. The promotion of interdisciplinary and multi-stakeholder relations (between the public and private sectors, contractors, consultants, nongovernmental) should take place in a participatory, interactive, and consensual manner.
4. The recognition of the complexity of the sustainability concept to make sure that alternative courses of action are compared. This is so that the project objectives and the stakeholders are satisfied with the final action implemented.
5. The use of a life cycle framework recognizes the need to consider all the principles of sustainable construction at each stage of a project's development (i.e., from the planning to the decommissioning of projects).
6. The use of a system's approach acknowledges the interconnections between the economics and environment. A system's approach is also referred to as an integrated (design) process.
7. That care should be taken when faced with uncertainty.
8. Compliance with relevant legislation and regulations.
9. The establishment of a voluntary commitment to continual improvement of (sustainable) performance.

10. The management of activities through the setting of targets, monitoring, evaluation, feedback, and self-regulation of progress. This iterative process can be used to improve implementation to support a continuous learning process; and
11. The identification of synergies between the environment and development [34].

The use of sustainable practices and an environmental evaluation during the planning and design phases of building projects will make up the framework for achieving sustainable construction. It will be applied to direct the building process across all levels and specialties. An infinite number of project- or discipline-specific principles and guidelines may be deduced from them, ensuring that decisions are made in a way that promotes sustainable development. Building professionals all around the world are starting to understand sustainability and the benefits of using sustainable practices in construction projects. For example, the concept of sustainable building costs lower than conventional method and saves energy as demonstrated by Hydes and Creech [35]. This was further supported by Pettifer, who added that sustainable buildings will contribute positively to better quality of life, work efficiency and healthy work environment. Pettifer explored the business benefits of sustainability and concluded that the benefits are diverse and potentially very significant [36].

3.2 Green building rating systems

Growing attention to global environmental and societal challenges requires the construction sector to be more sustainable, because of its major impact on these challenges. Beyond regulations and policy enforcements, a voluntary effort is required of all the stakeholders to design, construct, run and manage buildings assuming a holistic approach to sustainability. This requires that the effect of construction features on the triple bottom line (planet, people, profit), as well as possible mitigation actions, are clearly understood. Accordingly, sustainability assessment has been recognized as a crucial mean to this end [37] and Green Building Rating Systems (GBRSs) have emerged as a valuable tool to assess and guide the whole construction process to be greener [38].

A Rating System (RS) is a tool for classifying objects based on how well they comply with one or more relevant requirements, which are those that affect the object’s performance whose level the system is intended to appraise. A RS evaluating the level of sustainability of a building must consider several requirements, detecting the level of performance for each of them respect to a common baseline, which might be regulatory thresholds or a comparison benchmark with other buildings. In other words, a RS “rates or rewards relative levels of building performance or their compliance with specific environmental goals and requirements” [39].

In 1990, the Building Research Establishment (BRE) started a voluntary environmental assessment method (BREEAM). The purpose of the assessment method was to objectively measure the environmental performance of new and existing buildings in the United Kingdom. As the system evolved, goals were set for buildings to have a better rating. Instead of buildings simply being designed to meet code requirements, designers were striving to achieve improved building performance. The third-party assessment became a critical part of the assessment program as all buildings were held to the same standard. In the following years, BREEAM was introduced to other countries, including

Canada, Hong Kong, and New Zealand [40]. Rating systems have evolved based both on user feedback and the development of new technology to improve the environmental performance of buildings. Green rating systems started out as a voluntary measure of environmental performance. However, certification is now a mandate for buildings in many areas across the globe. Fifteen rating systems that offer certifications are currently available throughout the world and more are in development or pilot stages. These certifications are mentioned in the following figure.

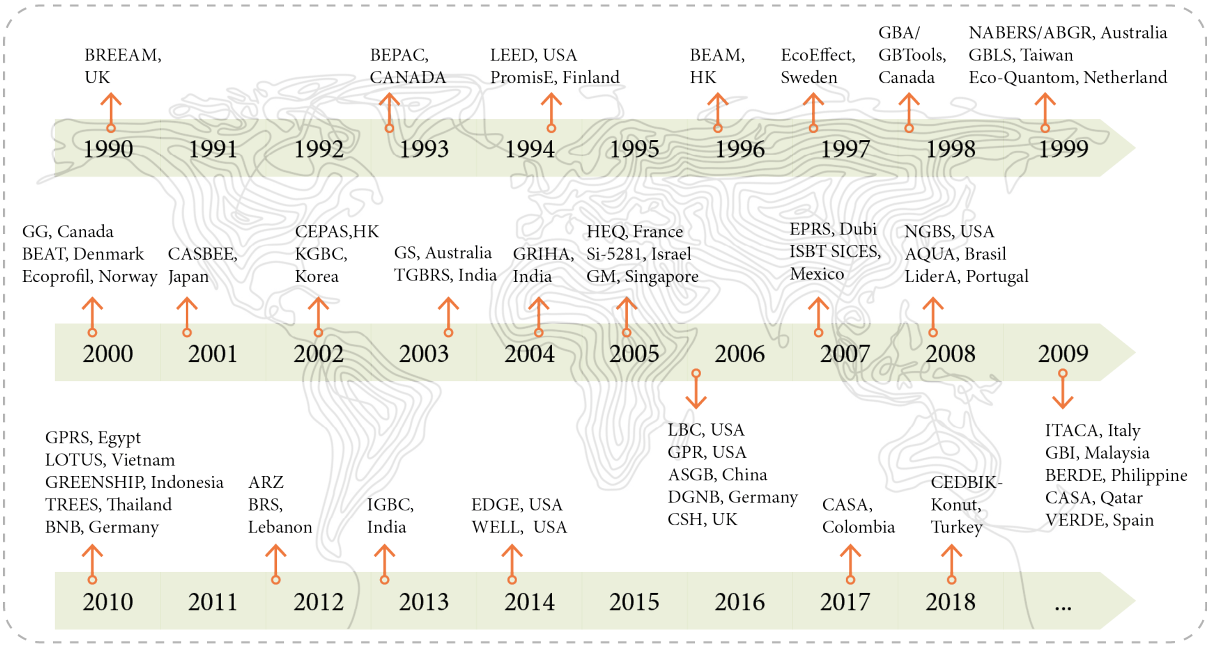


Figure 3- Rating systems timeline [41].

During this study, BREEAM, LEED, CASBEE, and Green Star NZ, were analyzed in detail. The rationale to select these rating systems is based on considering BREEAM, LEED, and CASBEE as globally well-known leading ones alongside Green Star NZ, which in comparison is a relatively new system that has recently released its latest version and New Zealand has subsequently seen a significant increase in the number of registered green buildings.

3.2.1 BREEAM

BREEAM is seen as the first green building rating assessment in the world, launched and operated by Building Research Establishment (BRE) in the UK Zealand [42]. It was introduced to the market in 1990 and was first revised to assess offices in 1993 Zealand [43]. It is widely accepted that almost all later major green rating systems such as LEED, Green Star, and CASBEE are under the influence of BREEAM (figure 3). BREEAM is widely used owing to its flexibility. It not only assesses local codes and conditions but also allows application in international buildings Zealand [44]. In addition, BREEAM enables evaluation of a building's lifecycle in view to design, built, operation and refurbishment; BRE provides New Construction, In-use, Refurbishment and Fit-Out, Communities, and Infrastructure manuals for planners, local authorities, developers, and investors. BREEAM certifications accounts for 80% of the European market share for sustainable building certifications Zealand [45]. The environmental aspect still dominates, with eight primary areas including Management, Energy, Transport, Water, Materials, Waste, Land Use & Ecology, and Pollution, even though BREEAM could assess all sustainability pillars.

3.2.2 LEED

LEED is a voluntary standard developed by USGBC (US Green Building Council). It was first launched in 1998 with a pilot version (LEED 1.0). Although it was released after BREEAM, it is considered as the most widely adopted rating scheme based on the number of countries, with over 79,000 projects across 135 countries in 2012, reaching nearly 150 countries and territories in 2014, and over 160 countries and territories at present. The square footage of LEED-certified projects has risen dramatically during 2008e2016 (approximately 100%), from around 0.15 billion to over 15 billion square feet. Like BREEAM, LEED predominantly evaluates environmental factors including Sustainable Sites, Water Efficiency, Energy and Atmosphere, Material and Resources, and Indoor Environment Quality categories. All the building's lifecycle could be evaluated based on the criteria from Building Design and Construction, Interior Design and Construction, Building Operations and Maintenance, Neighborhood Development manuals [46].

3.2.3 CASBEE

CASBEE was developed by the collaboration of academia, industry, and the local governments in 2001 in Japan. Owing to its limitation to Japanese context, the number of certified buildings is still modest (330 buildings since 2004). However, it is the rating which evaluates the broadest context and started releasing a pilot version for worldwide use in 2015. CASBEE could assess the buildings starting from the design to the renovation with criteria from CASBEE Buildings, CASBEE for Commercial Interiors, and CASBEE for Temporary Construction manuals. While CASBEE for Urban Development and CASBEE for Cities manuals are used as frameworks to evaluate a group of buildings [47].

3.2.4 Green star

The Green Star NZ rating scheme was first launched in 2007 by New Zealand Green Building Council (NZGBC), based on the Australian Green Star. Compared to the rating schemes above, Green Star NZ is the youngest. It is the only one that does not provide a manual to assess the building during its performance phase. Since it has been in the market for a decade only, the number of certified buildings is still limited. However, it has seen a positive trend to reach 125 certifications [47].

3.2.5 Comparison

General information of the green building rating systems compared in this study are presented in the following table. Different green building rating systems provide different categories of certification, hence different rating tools. The most common categories are the certification of new buildings, existing buildings, interiors, and communities, though some rating systems, particularly ASGB, GM, GBI and IGBC make a detailed distinction between the types of building (Table 3). CASBEE and IGBC differentiate communities into categories such as urban development, cities, residential societies, and green townships. This demonstrates a trend of increasingly specific rating systems to purpose-fit different types of development rather than a one-size-fit-all rating system [47].

GBRs	LEED	BREEAM	CASBEE	GS
Initiator	US Green Building Council	Building Research Establishment (BRE)	Japan Sustainable Building Consortium	Green Building Council Australia
Categories	Integrative Process Location and Transportation Sustainable Site Water Efficiency Energy and Atmosphere Material and Resources Indoor Env. Quality Regional Priority Innovation	New Construction Exist. Buildings Operations and Maintenance Comm. Interiors Core and Shell Schools Retail Healthcare Homes Neighbour. Develop	Indoor Environment Quality of Service On-site Environment Energy Resource and Materials Off-site Environment	Management Indoor Environment Quality Energy Transport Water Material Land Use and Ecology Emissions Innovation
Building Adaptations	New Construction Exist. Buildings Operations and Maintenance Comm. Interiors Core and Shell Schools Retail Healthcare Homes Neighbour. Develop.	New Construction In-Use Refurbish. and Fit-Out Communities	Pre-design New Construction Existing Building and Renovation	Communities Buildings Design and As Built Interiors Performances
Assessment Method	Additive credits	Pre-weighted categories	BEE ranking chart	Pre-weighted categories
Certification Levels	Certified 40–49 Silver 50–59 Gold 60–79 Platinum ≥80	Pass ≥30 Good ≥45 Very Good ≥55 Excellent ≥70 Outstanding ≥85	Poor: BEE < 0.5 Fairy Poor: BEE 0.5–1.0 Good: BEE 1–1.5 Very Good: BEE 1.5–3 or BEE ≥3 and Q < 50 Excellent: BEE _ 3 and Q ≥50	Min. Practice (1 star) Average Practice (2) Good Practice (3) Best Practice (4) Austria. Excellence (5) World Leader. (6)
Country	US	UK	JAPAN	AUS
Data source	[48]	[49]	[50]	[51]

Table 3- Comparison of GBRs (compiled by the author).

Given that the focus of this study is on building energy systems, many parameters in GBRs were reviewed in this part, and the critical parameters connected to the HVAC systems were identified and categorized into five categories, as shown in the following figure. It is considered that the final rating systems will be developed in the research's last chapter following the final LCA analysis, taking these categories into account.

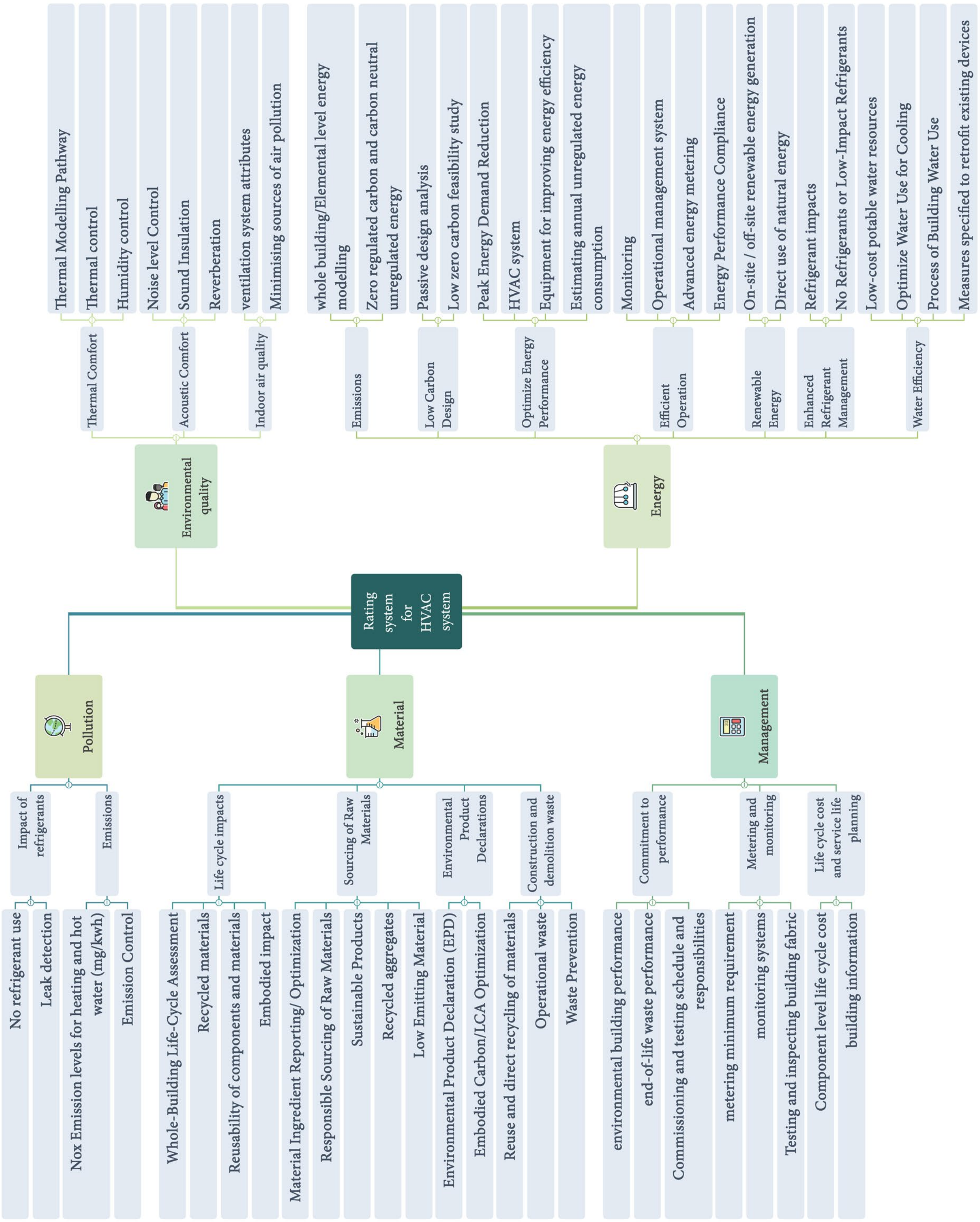


Figure 4- Derived criteria for HVAC rating systems from GBRs.

3.3 Heating, ventilation, and air conditioning systems

Building Energy Systems (BES) can be defined as those which are responsible for the consumption of energy in buildings. These can be any physical equipment or machinery or can be a process or a combination of them. Heating, Ventilation, And Air Conditioning (HVAC) system is designed to achieve the environmental requirements of the comfort of occupants and a process [52]. These systems have a large impact on the net energy consumption of buildings.

3.3.1 Classifications

HVAC systems may be generally classified as heating only, ventilating only, cooling only, or air-conditioning systems. The major classification of HVAC systems is the central system and the decentralized or local system. Types of a system depend on addressing the primary equipment location to be centralized as conditioning the entire building as a whole unit or decentralized as separately conditioning a specific zone as part of a building Local Systems [53].

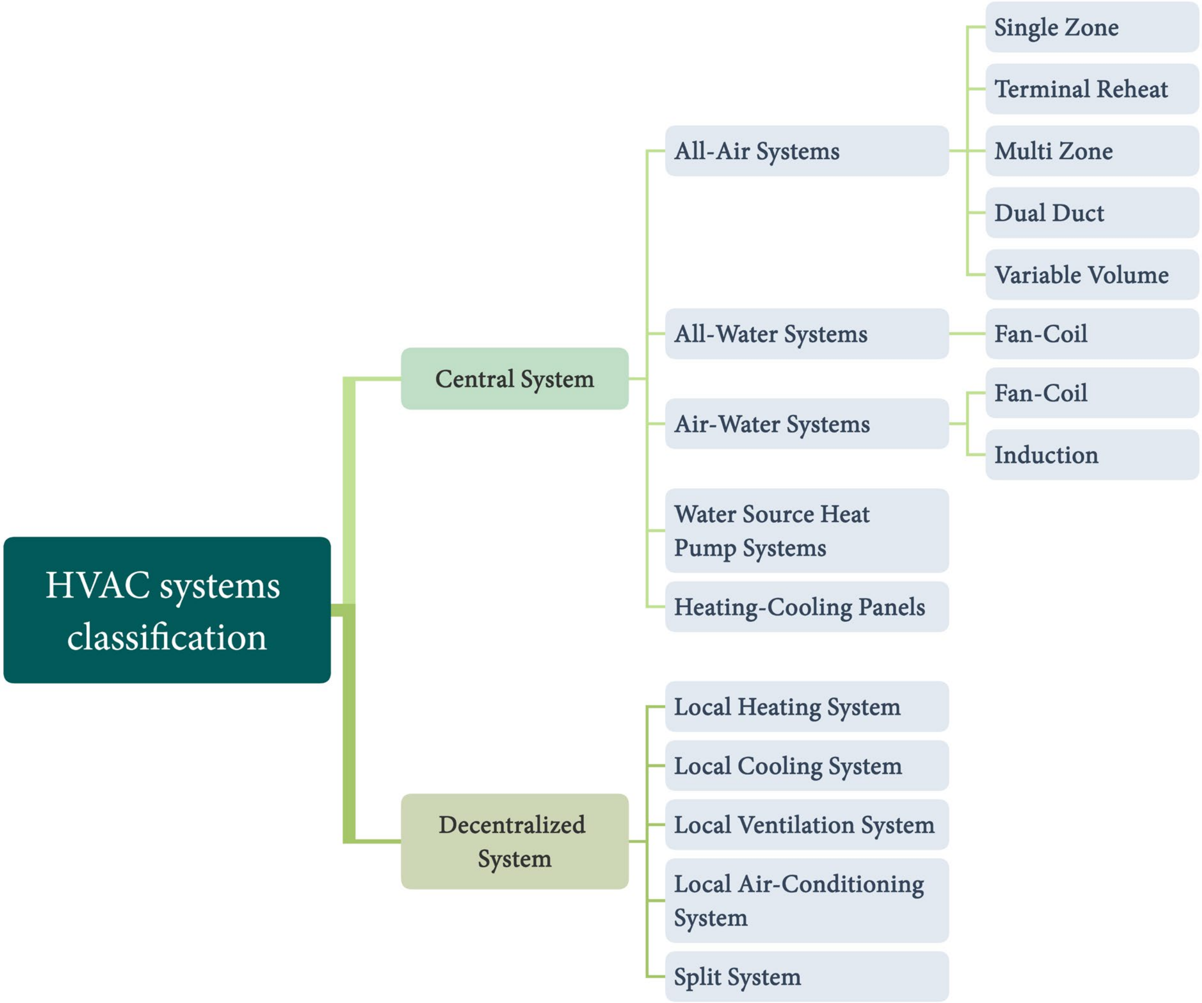


Figure 5- HVAC systems classifications [53].

3.3.1.1 Local systems

Some buildings can have multiple zones or have a large, single zone, which needs central HVAC systems serve and provide the thermal needs [53]. However, other buildings may have a single zone which needs equipment located inside the zone itself, such as small houses and residential apartments. This type of system is considered a local HVAC system since each piece of equipment serves its zone without crossing boundaries to other adjacent zones (e.g., using an air conditioner to cool down a bedroom, or using an electrical heater for the living room). Therefore, a single zone requires only a one-point control point connected to a thermostat to activate the local HVAC system. Some buildings have multiple local HVAC systems as proper equipment serving specific single zones and controlled by the one-point control of the desired zone. However, these local systems are not connected and integrated into central systems but are still part of a large full-building HVAC system [53].

3.3.1.2 Central systems

A central HVAC system may serve one or more thermal zones and has its major components located outside of the zone or zones being served, usually in some convenient central location in, on, or near the building. Space conditioning (thermal) energy from a central system must pass through zone boundaries on its way to the space or spaces being conditioned. Central HVAC systems will have as many points of control(thermostats) as there are zones. The nature of the thermal energy transfer medium used by a central system provides a means of sub-classifying central HVAC systems. If conditioning is transferred only by means of heated or cooled air, the system is termed an all-air system. If conditioning is transferred only by means of hot or chilled water, the system is termed an all-water system. If conditioning is transferred by a combination of heated/cooled air and hot/chilled water, then the system is termed an air-water system [53].

3.3.2 Heating, ventilation, and air conditioning systems components

The HVAC system components may be grouped into three functional categories: source components, distribution components, and delivery components. Source components provide or remove heat or moisture. Distribution components convey a heating or cooling medium from a source location to portions of a building that require conditioning. Delivery components serve as an interface between the distribution system and occupied spaces. Compact systems that serve only one space or zone of a building (local systems) often incorporate all three functions in a single piece of equipment. Systems that are intended to condition multiple spaces in a building (central systems) usually have distinctly different equipment elements for each function [53].

3.3.2.1 Source components

Four distinctly different types of heat sources are employed in buildings. Heat may be generated by the combustion of some flammable material (a fuel) such as coal or natural gas. Electricity may be converted to heat through the process of electric resistance. Solar radiation or other renewable energy resources may be collected on site and converted to heat. Heat may be removed from some material on site and transferred into a building. All four of these fundamental heat sources find common use in all scales of buildings. The choice of a heat source for a given building situation is usually based upon source availability, required system capacity, and equipment and fuel costs [53].

3.3.2.2 Distribution components

Central systems produce a heating and/or cooling effect in a single location. This effect must then be transmitted to the various spaces in a building that require conditioning. Three transmission media are commonly used in central systems: air, water, and steam. Hot air can be used as a heating medium, cold air as a cooling medium. Hot water and steam can be used as heating media, while cold water is a common cooling medium. A central system will always require distribution components to convey the heating or cooling effect from the source to the conditioned locations. Several piping materials are used in HVAC distribution systems. Steel pipes are by far the most common, although copper may be used when economic or environmental conditions dictate. Hot and cold (chilled)water pipes in HVAC distribution systems are normally insulated. Minimum insulation requirements are prescribed in energy codes and standards [53].

3.3.2.3 Delivery components

The heating or cooling effect produced at a source and distributed by a central system to spaces throughout a building needs to be properly delivered to each space to promote comfort. In air-based systems, heated or cooled air could theoretically just be dumped into each space. Such an approach, however, does not provide the control over air distribution required of an air-conditioning system. In water-based systems, the heated or cooled media (water or steam) cannot just be dumped into a space. Some means of transferring the conditioning effect from the media to the space is required. Devices designed to provide the interface between occupied building spaces and distribution components are collectively termed delivery devices [53].

4 Life cycle assessment methodology

Life Cycle Assessment (LCA) is a process whereby the material and energy flows of a system are quantified and evaluated. Typically, upstream (extraction, production, transportation, and construction), use, and downstream (deconstruction and disposal) flows of a product or service system are inventoried first. Subsequently, global and/or regional impacts (e.g., global warming, ozone depletion, eutrophication, and acidification) are calculated; based on energy consumption, waste generation, etc. LCA allows for an evaluation of impacts of different processes and life cycle stages on the environment [54].

As per international organization for standardization, LCA studies generally consist of four phases: goal and scope definition, Life Cycle Inventory (LCI), impact assessment and interpretation of results. The goal and scope define the purposes, audiences, and system boundaries. The LCI involves data collection and calculations to quantify material and energy inputs and outputs of a system, and the impact assessment evaluates the significance of potential environmental impacts based on the LCI. To use LCA methods to assess the environmental impact, it is necessary to perform an inventory analysis. However, in the construction industry, the materials used in construction, operation, and demolition are varied and the range of environmental criteria that are relevant to buildings is potentially enormous. This may serve as a severe limitation to the use of LCA methods in the building industry [55].

Life cycle assessment has been used in the building sector since 1990 and has also been used to assess product development processes from cradle to grave for many years. With the current push toward sustainable construction, LCA has gained importance as an objective method to evaluate the environmental impact of construction practices [56]. Commonly used life cycle impact categories are defined in the following table.

Impact category	**Scale**	**Relevant LCI data**	**Common characterisation factor**	**Description of characterisation factor**
Global Warming	Global	Carbon Dioxide (CO_2)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents
		Nitrous Oxide (N_2O)		
		Methane (CH_4)		
		Chlorofluorocarbons (CFCs)		Note: Global warming potentials can be 50, 100/500-year potentials
		Hydrochlorofluorocarbons (HCFCs)		
		Methyl Bromide (CH3Br)		
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents
		Hydrochlorofluorocarbons (HCFCs)		
		Halons		
		Methyl Bromide (CH_3Br)		
	Regional	Sulphur Oxides (SOx)		

Acidification	Local	Local Nitrogen Oxides (NO_x)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents
		Hydrochloric Acid (HCL)		
		Hydrofluoric Acid (HF)		
		Ammonia (NH_4)		
Eutrophication	Local	Phosphate (PO_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents
		Nitrogen Oxide (NO)		
		Nitrogen Dioxide (NO_2)		
		Nitrates		
		Ammonia (NH_4)		
Photochemical Smog	Local	Non-methane volatile organic compounds (NMVOC)	Photochemical Oxidant Creation Potential	Converts LCI data to ethane (C_2H_6) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC50	Converts LC50 data to equivalents.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC50	Converts LC50 data to equivalents
Human Health	Global	Total releases to air, water, and soil.	LC50	Converts LC50 data to equivalents
	Regional			
	Local			
Resource Depletion	Global	Quantity of minerals used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve
	Regional	Quantity of fossil fuels used		
	Local	-		
Land Use	Global	Quantity disposed of in a landfill	Solid Waste	Converts mass of solid waste into volume using an estimated density

Table 4- Commonly used life cycle impact categories; adapted from US EPA guidelines and principles [57].

As shown in the following figure, to clarify the life cycle phases, the embodied carbon may be reported as “cradle to gate”, “cradle to site”, “cradle to service” or “cradle to grave”.

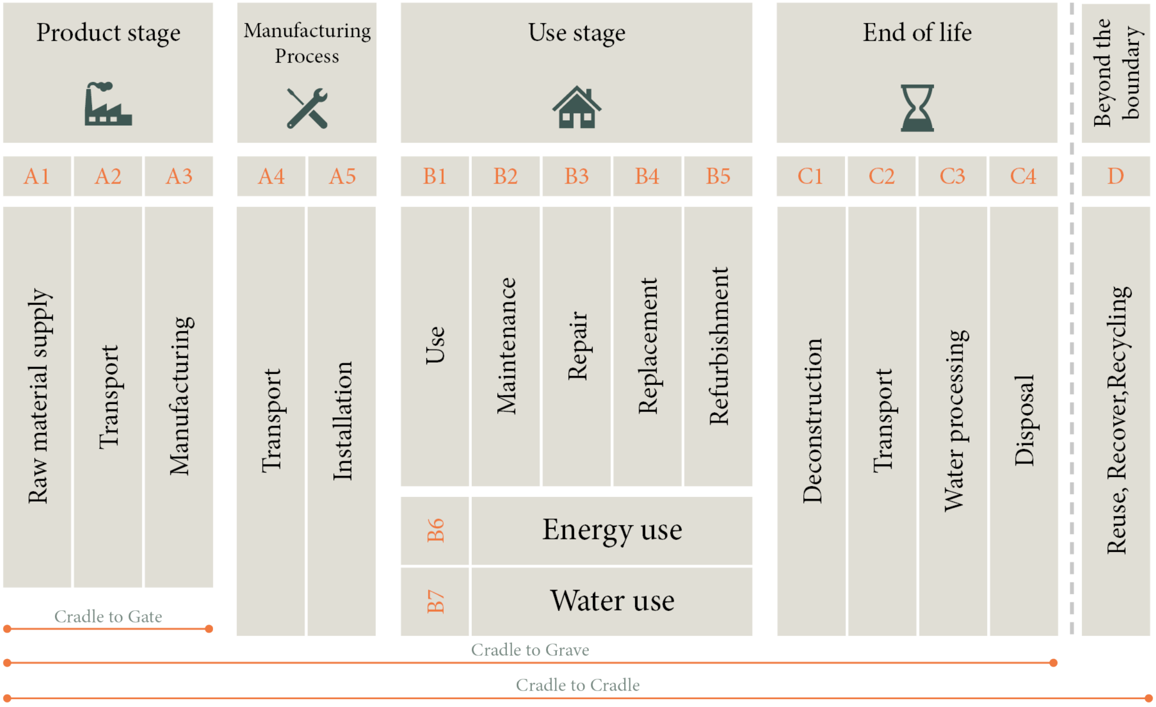


Figure 6- System Boundary: EN 15978:2011, Distinct stages of the building assessment.

4.1 life cycle assessment of building energy systems

Between 1990 and 2008, world energy consumption increased by 40%. Today, 68% of the energy utilized worldwide originates from fossil fuels (i.e., coal, natural gas, and oil), with electricity generation being responsible for 40% of global CO_2eq emissions. Emissions of Green House Gases (GHG), such as CO_2eq and CH_4, from energy generation have been addressed in numerous studies, which often play a key role in developing GHG mitigation strategies for the energy sector [58]. A variety of factors can affect the carbon emission of an HVAC system during its service life. The lifespan of HVAC is composed of a series of interlocking processes, starting from initial design and manufacture, through to actual construction, and then to annual operation and maintenance, as well as to eventual demolition or renovation. The construction of HVAC has a very important impact on the environment, and it is one of the greatest consumers of resources and raw materials in HVAC construction [59]. The manufacture and transportation of HVAC materials and products, and the installation and construction of HVAC components consume great quantities of energy and emit large amounts of carbon dioxide. Four distinct phases: manufacture, construction, operation and maintenance, and demolition are included in life cycle stages of HVAC system.

The manufacture stage is the phase of production of HVAC materials and three major activities occur in this stage. The first procedure in the material production is the extraction of raw materials, for example drilling for oil, mining for iron ore, or harvesting wood. The energy used to acquire raw materials is the initial embodied energy of the iron, copper, and aluminum materials for the HVAC systems. The second procedure in the manufacture phase is the refinement of raw materials into engineered HVAC products, such as the extrusion of steel or aluminum and the injection modelling of plastics. The last procedure is the transportation, which covers shipping of HVAC materials from the source to the manufacturing site. The carbon emission from the transportation is the fuel consumption for delivering HVAC products. The embodied energy is therefore the sum of energy expended during raw materials extraction, the processes of HVAC product refinement and production, and the transportation from source to the manufacturing site [*61*].

The construction stage is the phase of installing the comprehensive HVAC products in unequipped buildings, to produce the mechanical service as a function of heating, cooling, and ventilation. The carbon emissions in this phase comprise two parts:

1. the transportation type used to transport the HVAC products from the manufacturing factory to the construction site.
2. the electricity consumed for power tools and lighting, as well as heavy equipment at the construction site [61].

The construction processes involve the use of construction equipment, e.g., cranes hoist HVAC products, and hammers for pile-driving. Most of the HVAC installation work, including the installation of ducts, air outlets, chilled beams, air diffusers, and thermal insulation, is undertaken by manual workers [61].

The operation stage activities consist of heating, cooling, and ventilating the building. Carbon emissions are mainly from the electricity consumption of HVAC services. Maintenance and renewal occur periodically over the life of HVAC systems and are assumed to involve replacing less than 100% of a HVAC product. Maintenance and renewal can be categorized into two types as follows [60]:

Maintenance incurred during a completed life cycle of a HVAC product. For a HVAC product which completes its life cycle, the number of maintenance or repairs required is the product life divided by repair interval corrected for the possibility of forgone repairs near the end of the product's life; Renewal incurred during the incomplete life cycle of a product due to the expiration of the HVAC. The renewal rates will depend on the service life of the HVAC system [61].

However, most LCA studies have the tendency to reduce the system boundaries to the main construction materials of a building, leaving on the side the HVAC systems. These systems are usually quite complex, made of many different materials, and itis difficult to quantify the total mass of the materials from plans as usual LCA are carried. Very few studies include detailed HVAC system calculation in their LCA. Furthermore, despite the increasing number of LCA studies which make use of building information modelling, HVAC systems are neglected. This leaves a knowledge gap regarding the embodied impact of HVAC systems and therefore a blind spot in the building's overall embodied carbon footprint. Most studies examine the environmental impact of the structural elements and the building envelope. Only a few studies focus on the impact of building services, including HVAC systems.

Structural composition of a life cycle assessment process

Using the LCA model, Lee et al. [62] point out that the requirements of an LCA program need to fulfil the following information in order to be considered valid. Firstly, it must include all activities in an HVAC life cycle which are categorized as the manufacturing stage, the construction stage, the operation and maintenance stage, and the demolition stage. Most existing LCA programs are designed to evaluate each stage separately for an individual product. Secondly, the results of the LCA program should be presented in several ways according to the term, which is being evaluated, for example, energy consumption or carbon emissions as CO_2eq.

Finally, it is important to select a purpose or scope for the assessment. The scope of the life cycle process in HVAC systems should be limited to the HVAC materials and products required for the building, construction activities, energy requirements, modification work, and demolition requirements. CO_2eq emission assessment is a purpose related to the energy consumed during the process of an HVAC life cycle. Based on the three main components for a LCA as outlined above, the structural component of its program can be described as follows. Firstly, the next figure illustrates the HVAC life cycle process divided into the stages of its manufacture, construction, operation and maintenance, and demolition. It also depicts what is included at each stage. For example, the carbon emissions during the manufacture stage would be related to the energy consumed in production and in transportation. In the construction stage, the electricity consumed by equipment should be taken into consideration. In the operation & maintenance stage, the necessary modification and repair works are determined by the HVAC performance efficiency and age. Those modification and repair works will consume extra HVAC products and materials due to the scale of the maintenance activities [62].

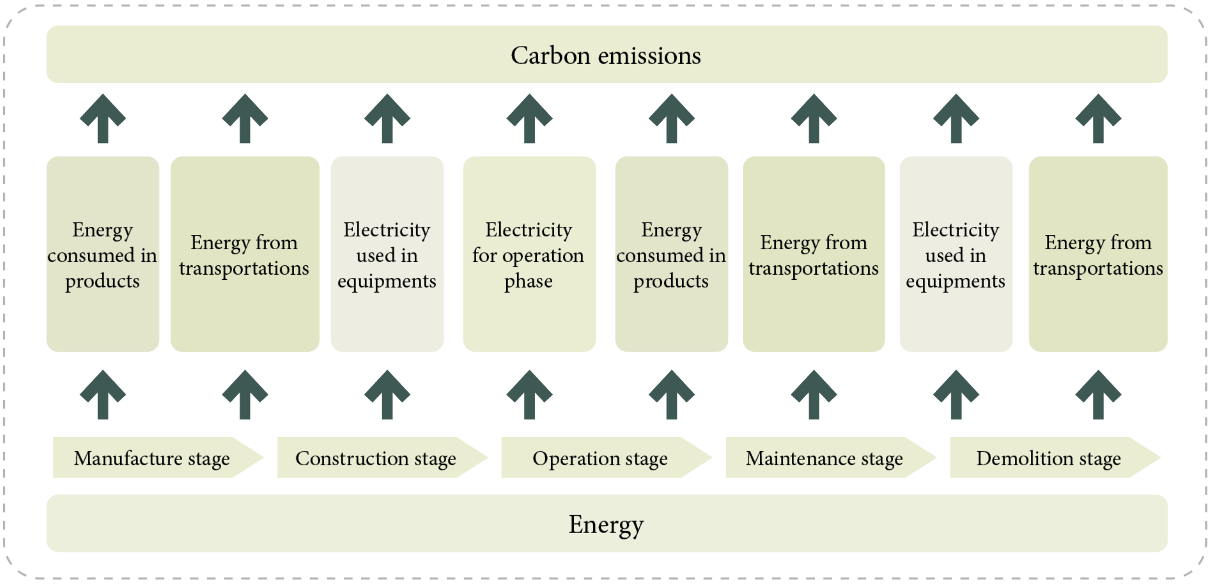


Figure 7- Boundaries of LCA [60].

The extra energy used for transportation and equipment are also included. An example for the demolition stage is the transportation required. Secondly, the method of analysis for the LCA should be undertaken in each stage of the life cycle. Available databases for HVAC materials and products, construction activities, energy consumption, and demolition stages are not comprehensive. It is difficult to establish from a single method of approach. In each stage, different methods are appropriate to be used to calculate the carbon emission with data coming from different database resources. To prepare LCA for the modification and repair part of the operation and maintenance stage, a database to quantitatively express a HVAC's rate of deterioration, and the repair levels commensurate with aging, is needed. It is also necessary to develop a dynamic model to predict the carbon emissions based on the life cycle activities. The dynamic model will give a better understanding of the HVAC performance in the life cycle process. Furthermore, those dynamic models will contribute to motivating more environmentally sustainable design and construction strategies [62].

4.2 Life cycle assessment of temporary buildings

In the last decade, the demand for temporary structures is expanding because of the growing of world events, artistic and sport programmers, festival, fairs, etc. These buildings had to respond to sustainable design rules in term of flexibility, speed of execution and low budgets. There are several limits to achieve good results (no thermal and acoustic insulation, use of multifunctional structure not suitable for a special function, etc.). Since temporary buildings are exempted from the application of minimum requirements to reduce energy in use as set by the European directive 2010/31/EU due to their short, expected service life, it becomes even more important to consider the impact of their embodied energy and the one of their ends of life [63]. When designing temporary structures, which must be erected and dismantled regularly, costs, weight and the size of the prefabricated components must be limited [64]. Temporary buildings for mega events are buildings with a short service life strictly related to the event duration. Estimates of energy performance of a building during its life cycle include the amount of energy needed for heating, cooling, ventilation, hot water, and lighting as well as the embodied energy of construction materials. In this perspective, building expected service life must be considered since the earlier design phases [64].

4.2.1 Environmental assessments methodology

A critical first step for the development of the methodology for assessing the environmental performance of temporary buildings in mega events is to define the types of temporalities associated with the mega events and the possible end of life scenarios, correlating them with constructive and technological design solutions. With the aim of the mitigation of environmental impacts, it is clearly unsustainable designing disposable temporary buildings; instead, the temporary nature must be designed as the possibility of extending to more uses and more lives the constructed object. In the first two cases, the temporary nature of the building shall be a requirement in the design phase, an upstream objective of the project since it requires the project to deal with the functionality of the second life and with technical characteristics that allow the reuse. In this perspective, the temporariness of the buildings related to mega events, can be defined as [65]:

1. Temporary placement/location (with the disassembly and reassembly of the entire structure or of its parts separately elsewhere at the end of the event).

2. Temporary function (with the re-functionalization of the structure for a new use at the end of the event).
3. Temporary life (with the demolition at the end of the event and waste treatment without reuse of the building parts).

In the first two cases, the temporary nature of the building shall be a requirement in the design phase, an upstream objective of the project since it requires the project to deal with the functionality of the second life and with technical characteristics that allow the reuse. The temporary placement consists in the construction of temporary buildings, for example for exposition purposes as in the case of the Expo, which are then disassembled and relocated to meet the new requirements of use. A recent example of temporary placement is the Christ Pavilion designed by von Gerkan, Marg und Partner for the Expo 2000 in Hannover, and relocated to Volkenroda [66].

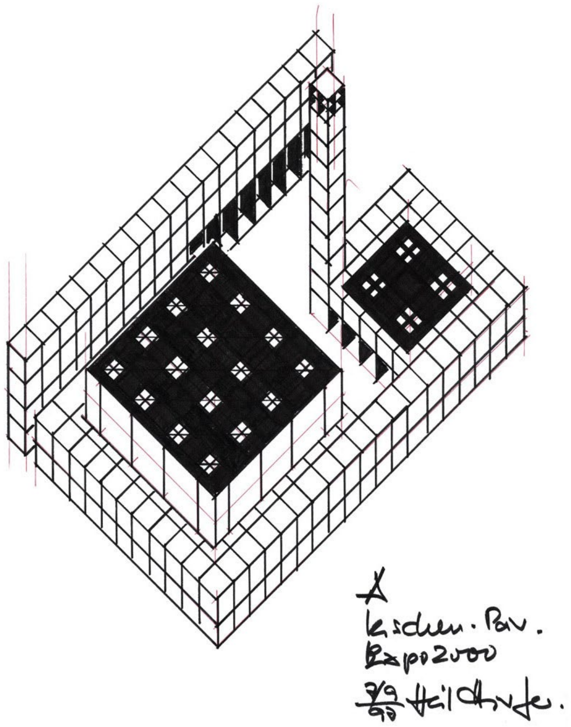


Figure 8- Christ Pavilion, Volkenroda, Körner, Germany [66].

The temporary nature of function is characterized by the construction of permanent buildings, in which are allocated temporary functions during the event and that are functionally reconverted after the event, with a target useful to society. An example of a temporary function is the Turin Olympic Village, built for the 2006 Winter Olympics to accommodate delegations, and converted at the end of the event in social housing. In both cases, the temporary nature must be thought in the design phase, so to be an upstream objective of the project since it requires the project to deal with the functionality of the second life.

Moreover, the objective is the realization of a structure used temporarily for the event, but physically durable and reused after the event. Thinking about a "durable" temporariness, which is guaranteed by the extension of the useful life of the building, is a sustainable objective, not just from an environmental perspective, but also social (because it allows you to create useful equipment for the society), and economic (by enhancing the use value and the economic potential value of the structure) [66].

The possible scenarios at the end of the first use (after the event) of the temporary building are:

1. Reuse of the whole building for a similar/compatible use (re-functionalization without modification) in the same place.
2. Reuse of the whole building for the same use in another place (relocation).
3. Reuse of the whole building for a different use (re-functionalization with modification) in the same place.
4. Reuse of the whole building for a different use (re-functionalization with modification) in 94 another place (relocation).
5. Disassembly of the building and reuse of the divided building components for the same use.
6. Disassembly of the building and reuse of the divided building components for other use.
7. Demolition of the building and disposal/energy recovery/recycling of building materials.
8. Landfill [67].

Partial reuse is also possible, with a mix of the previous scenarios. Clearly, these different scenarios have different environmental and economic value associated with them and in the case of the temporary nature it is important to spread the scenarios of reuse. But the actual feasibility of the different scenarios basically depends on the technical and material choices of the project (construction with mechanical connections dry assembled, constructive reversibility and separability of materials, use of recyclable materials, etc.). In relation to the solutions used in the project is thus possible to delineate the possible end of life scenarios and to associate the corresponding environmental impacts [67].

4.2.2 Purpose of the assessment

The purpose of the assessment is defined by the goal, the scope, and the intended use of the assessment. The goal of the assessment is to quantify the environmental performance of the temporary building by means of the compilation of environmental information. To calculate the environmental performance of the building in terms of environmental impacts and aspects, the scope and intended use of the assessment shall be defined and documented. The scope of the assessment is represented by what is included in the assessment with respect to the specifications of the object, i.e., the temporary building, to the quantification of the building and its life cycle, to the type of data. In particular, the scope and the intended use determine the level of detail required of the environmental information, and of other data used in the calculations. However, the calculation method remains the same [67].

Depending on the context, the intended use of the assessment may include the following alternatives:

1. assistance in a decision-making process, for example:
   (a) Comparisons of the environmental performance of different design options for temporary buildings (e.g., alternative materials, products, technical solutions).

(b) Comparisons of the environmental performance of the different scenarios post-event of the temporary building (e.g., demolition and reconstruction, relocation, and reuse of the building in another place, on site re-functionalization of the building).
(c) Identification of the potential for environmental performance improvements.

2. declaring performance with respect to legal requirements or for acquiring access to incentives (e.g., Green Public Procurement, minimum requirement in a tender).
3. documenting the environmental performance of a building for use in, for example:
   (a) Certification/labeling of the building (e.g., LEED, EPD of the building).
   (b) declaring environmental performance (e.g., award for sustainability of the organizer of the mega event).
   (c) Marketing.
4. Support for policy development [68].

4.2.3 Life cycle stages for the temporary scenarios

Based on the declared possible scenarios at the end of the first use (after the event) of the temporary building in section 4.2.1, focusing on the required HVAC systems during the period of events, the process of assessment would be defined. The core process of assessment is defined for the building's HVAC systems. The assessment includes all the upstream and downstream processes needed to establish and maintain the function of the building, in the first use and in the following uses. The following diagram illustrates the predicted life cycle stages for the building energy services which would be applied in temporary buildings during the events and after that.

In the first life, the product stage, manufacturing process and use phase are considered. It means that the manufactured product will transfer to the consumer and after finishing the operation phase by the first user, will enter its second life (second user). This procedure will continue until delivered to the last user which forms the last diagram (n° Use). After the operation period in the last life of the product, it would be conducted towards the end of life. Depending on the considered strategies for end of life, the product could be disposed of or according to the circular economy, it could be reused, recycled, or reclaimed.

It is notable that this diagram is defined based on the research assumption and would be re-defined if the stages are changed. the main parts of each life are specified. in the following chapter, detailed scenarios which are considered in this research will evaluate.

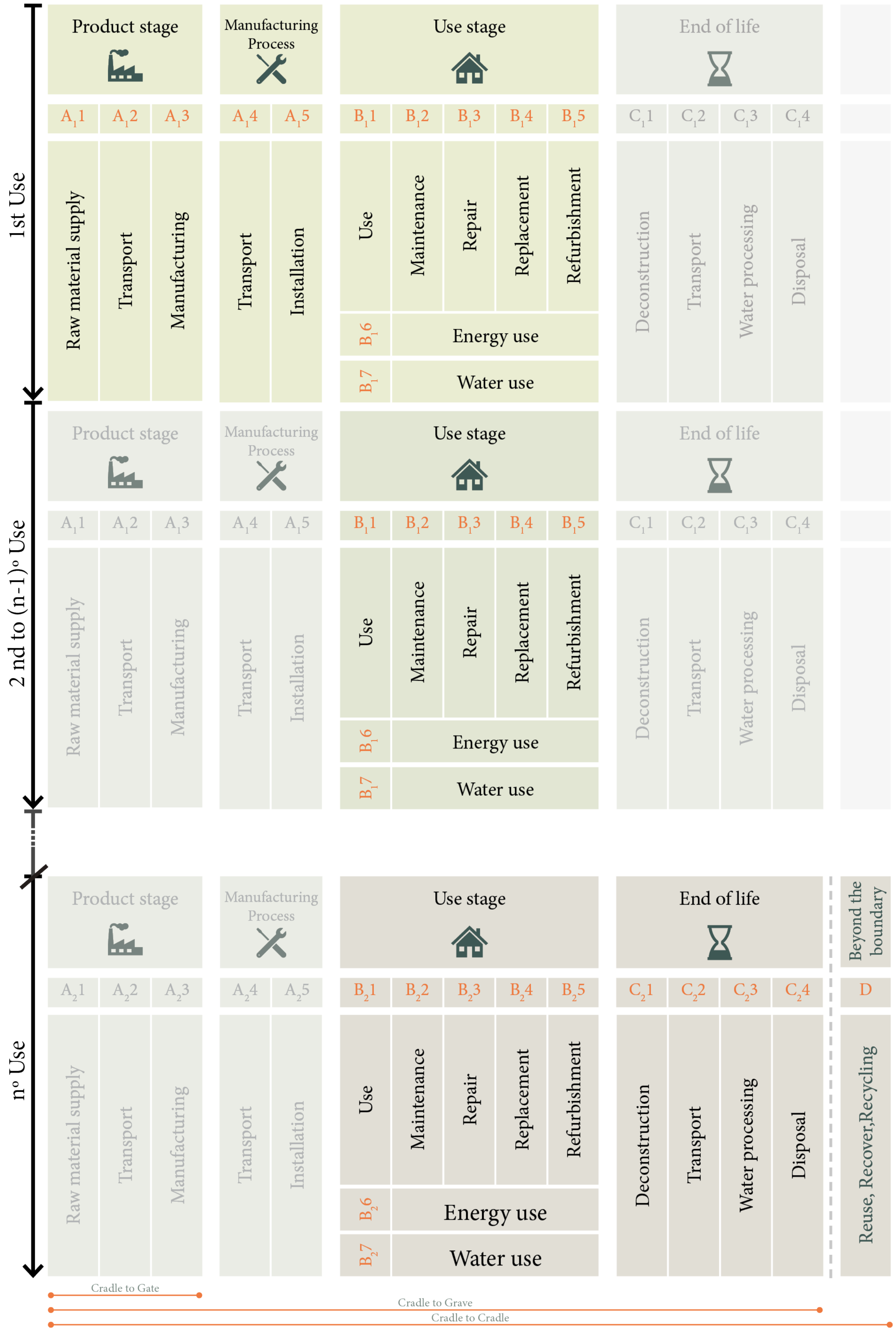


Figure 9- Different stages of the life cycle assessment of HVAC systems with temporary operations.

5 Case studies

Collected information and calculations are carried out during this section to quantify the system under study's inputs and outputs. Energy, raw materials, manufacturing process of products, waste, and emissions into the air, water, and land are examples of inputs and outputs. The input/output data is then arranged according to the phases and functional units of the process. ecoinvent v3 was used as the secondary data database.

At first, two types of energy systems (HVACs) as a case study and the quantity of heat generated is introduced. It is noticeable that the hypothetical condition for both device's installation is considered the same. Secondly, 4 types of business model according to the circular economy strategies are provided to investigate how the environmental impact could be changed and which parameter could be affected to these variations. All the analysis were carried out by SimaPro 9.4.0.1 Educational under the method of EN 15804 + A2 Method V1.03 / EF 3.0 normalization and weighting set.

5.1 Case studies

In this study, the following two sorts of energy systems were chosen: Natural Gas Boiler (NGB) and Electric Heat Pump (EHP). It should be noted that all external conditions are assumed to be equal to have a reasonable comparison based on LCA studies.

5.1.1 Natural gas boiler

Gas boilers are central heating systems that act like mini fires, continuously heating water. This heated water is then pumped around the property through pipes and radiators to heat space, and either pumped directly to taps and showers or stored in a hot water tank for future water usage. This gas is then burned in the boiler's combustion chamber and warms the water to around 70°C through a heat exchanger.

The analysis for this study was conducted using a natural gas boiler with a nominal gas input of 10 kW and the Higher Heating Value (HHV) of natural gas and SCOP of the boiler is assumed 83%. By obtaining primary information on the number of components and material types from a global boiler manufacturer, the Life Cycle Inventory (LCI) of the boiler was completed. Based on several publications, further information about manufacturing procedures, input and output transit, packaging, and end-of-life scenarios was gathered

Table 5 provides a description of the various activity data that were used for the evaluation. While ecoinvent v3 served as the reference background database.

Characteristic	Amount	Unit	Source
General information			
Thermal energy produced in life span	2 227.5	kWh	-
Nominal heat input	10	kW	-
Efficiency (HHV)	83%		Manufacturer data
Lifespan	2	Months	-
Surface	150	m^2	-
Energy needs	89.1	kWh / m^2 /y	Assumption
HHV	11.2	kWh / Nm^3	-
Mass	36	Kg	-
Components (A1-A3)			
Reinforced Steel	5.62E+00	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Steel low-alloyed	1.92E+01	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Aluminium	4.61E+00	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Elastomer	1.08E-02	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Polyvinylchloride	1.08E-01	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
ABS	2.34E+00	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Copper	3.53E+00	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Electronic components	1.00E+00	kg	Assumption based on Kemna et al. 2019 ecoinvent
Manufacturing process (A1-A3)			
Welding	4.00E+00	kg	As interpolation of ecoinvent data
Water consumption	1.82E+02	kg	As interpolation of ecoinvent data
Emissions of water in air	2.73E+01	m^3	ecoinvent
Emissions of water in water	3.64E+00	m^3	ecoinvent
Wastewater treatment	1.51E+02	m^3	ecoinvent
Electricity	2.12E+01	kWh	ecoinvent
Heat	1.85E+02	MJ	ecoinvent
Hazardous waste	2.00E-01	kg	Based on ecoinvent data
Transport input	1.08E+01	tkm	Keman et al. 2019
	2.52E+01	tkm	Keman et al. 2019
Packaging			
Plastic film	1.96E-01	kg	Keman et al. 2019
Polystyrene	9.80E-02	kg	Keman et al. 2019
Corrugated board	1.96E-01	kg	Keman et al. 2019
Distribution			
Transport from manufacturer to consumer	1.82E+01	tkm	Keman et al. 2019
	7.30E+00	tkm	Keman et al. 2019
	1.82E+00	tkm	Keman et al. 2019
Use phase (B6)			
Electricity	3.03E+01	kWh	Famiglietti et al. 2021b
Natural gas	2.40E+02	Nm^3	-
Emission to air during the combustion	9.66E-06	kg	ecoinvent
Emission to air during the combustion	1.45E-03	kg	ecoinvent
Emission to air during the combustion	3.86E-03	kg	ecoinvent
Emission to air during the combustion	9.66E-08	kg	ecoinvent
Emission to air during the combustion	6.76E-03	kg	ecoinvent
Emission to air during the combustion	5.22E+02	kg	ecoinvent
Emission to air during the combustion	2.90E-01	kg	ecoinvent
Emission to air during the combustion	4.83E-03	kg	ecoinvent
Emission to air during the combustion	9.66E-04	kg	ecoinvent

Emission to air during the combustion	2.90E-07	kg	ecoinvent
Emission to air during the combustion	1.93E-02	kg	ecoinvent
Emission to air during the combustion	1.93E-01	kg	ecoinvent
Emission to air during the combustion	9.66E-05	kg	ecoinvent
Emission to air during the combustion	9.66E-04	kg	ecoinvent
Emission to air during the combustion	1.16E-02	kg	ecoinvent
Emission to air during the combustion	1.93E-03	kg	ecoinvent
Emission to air during the combustion	1.93E-04	kg	ecoinvent
Emission to air during the combustion	4.83E-03	kg	ecoinvent
Emission to air during the combustion	1.93E-03	kg	ecoinvent
Emission to water during the combustion	1.26E-03	kg	ecoinvent
Emission to water during the combustion	2.90E-05	kg	ecoinvent
Emission to water during the combustion	4.83E-04	kg	ecoinvent
Emission to water during the combustion	4.83E-04	kg	ecoinvent
Maintenance (B2)			
Components substitution	-		Keman et al. 2019
Transport to consumer	4.17E-02	tkm	Keman et al. 2019
End of life (C2 – C4)			
Copper	3.42E+00	kg	Keman et al. 2019
	1.06E-01	kg	Keman et al. 2019
Steel	2.40E+01	kg	Keman et al. 2019
	7.43E-01	kg	Keman et al. 2019
Aluminium	4.47E+00	kg	Keman et al. 2019
	1.38E-01	kg	Keman et al. 2019
Plastic	1.72E+00	kg	Keman et al. 2019
	7.38E-01	kg	Keman et al. 2019
Electronic components	6.70E-01	kg	Keman et al. 2019
	3.30E-01	kg	Keman et al. 2019
Packaging cardboard	1.63E-01	kg	Keman et al. 2019
	1.13E-02	kg	Keman et al. 2019
	2.15E-02	kg	Keman et al. 2019
Packaging plastics	9.38E-02	kg	Keman et al. 2019
	6.87E-02	kg	Keman et al. 2019
	1.31E-01	kg	Keman et al. 2019
Transport from consumer to treatment plant	1.82E+00	tkm	Famiglietti et al. 2021

Table 5- Activity data and references for the NGB (LS.2m).

The system boundaries of material production include: the extraction of raw materials and primary components such as electronic components, transport to the manufacturing plant, production processes, and packaging and storage. Apart from Acrylonitrile-butadiene-styrene copolymer, all materials are represented by a process from the ecoinvent v3 European or global market database, which includes stage A1. In addition, an average distance of 1000 km for transport input and 700 km plus 50 km of transportation distance from manufacturing plant to building site (consumer) were assumed for all materials and components.

The ecoinvent processes which was run by SimaPro assigned to represent production to use phase of all NGB materials (A1-B7) are listed in the succeeding table.

Activity Data	Secondary Data	Mass/ Energy	Unit
Resources: material/fuels (A1)			
Reinforced Steel	Steel, chromiumsteel18/8, hot rolled {GLO}|market for| Cut-off, S	5.62	kg
Steel low-alloyed	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, S	19.20	kg
Aluminum	Aluminum, cast alloy {GLO}| market for | Cut-off, S	4.61	kg
Elastomer	Polyethylene, high density, granulate {GLO}|market for | Cut-off, S	0.01	kg
Polyvinylchloride	Polypropylene, granulate {GLO}| market for | Cut-off, S	0.10	kg
ABS	Acrylonitrile-butadiene-styrene copolymer {RER}| production | Cut-off, S	2.34	kg
Copper	Copper {GLO}| market for | Cut-off, S	3.53	kg
Electronic components	Electronics, for control units {GLO}| market for | Cut-off, S	1.00	kg
Input from Technosphere: Electricity/Heat (A2, A3, A4, B1, B2, B6)			
Welding	Brazing solder, cadmium free {GLO}| market for | Cut-off, S	4.00	kg
Hazardous waste	Process-specific burdens, hazardous waste incineration plant {Row}| market for process-specific burdens, hazardous waste incineration plant | Cut-off, S	0.20	kg
Water consumption	Tap water {Europe without Switzerland} | market for| Cut-off, S	181.99	kg
Electricity	Electricity, medium voltage {IT}| market for | Cut-off, S	21.24	kWh
Heat	Heat, district, or industrial, natural gas {CH}| market for heat, district, or industrial, natural gas | Cut-off, S	185.4	MJ
Transport input	Transport, freight train {Europe without Switzerland} | market for | Cut-off, S	10.80	tkm
	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	25.20	tkm
Plastic film	Packaging film, low density polyethylene {RER}| production| Cut-off, S	0.19	kg
Polystyrene	Polystyrene, expandable {GLO}| market for | Cut-off, S	0.09	kg
Corrugated board	Corrugated board box {RER}| market for corrugated board box | Cut-off, S	0.19	kg
Transport from manufacturer to consumer	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5|Cut-off, S	18.24	tkm
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5|Cut-off, S	7.30	tkm
	Transport, freight, light commercial vehicle {Europe without Switzerland} | market for transport, freight, light commercial vehicle | Cut-off, S	1.82	tkm
Electricity	Electricity, low voltage {IT}| market for | Cut-off, S	30.30	kWh
Natural gas	Natural gas, low pressure {Row}| market for | Cut-off, S	221.47	m^3
Transport to consumer	Transport, freight, light commercial vehicle {Europe without Switzerland} | market for transport, freight, light commercial vehicle | Cut-off, S	0.04	tkm
Transport from consumer to treatment plant	Municipal waste collection service by 21 metric ton lorry {GLO}| market for | Cut-off, S	1.82	tkm

Table 6- Activity mapping of SimaPro process (production phase of NGB).

The End Of Life (EOL) stage was modelled so that burdens and benefits of recycling, landfill and incineration were analysed through this stage. This provides a clearer view on how they contribute to the total impact. The system boundaries for EOL stage (C1-C4) for the NGB system include transportation from consumer to treatment plant (50 km), treatment of the materials and disposal of residual inert material. Once treated at the sorting plant, waste materials can either go to landfill, incineration, or recycling/reuse facility. There is a degree of uncertainty introduced when using the recyclability rate of construction materials. Data on this is scarce and there is always a level of uncertainty depending on the data source itself. Ecoinvent processes used to simulate the end-of-life stages of NGB system is presented in the following table.

Activity Data	**Secondary Data**	**Mass/ Energy**	**Unit**
	Waste treatment (C2 – C4)		
Copper	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S	3.42	kg
	Scrap copper {CH}| market for scrap copper | Cut-off, S	0.10	kg
Steel	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S	24.02	kg
	Scrap steel {Europe without Switzerland} | treatment of scrap steel, inert material landfill | Cut-off, S	0.74	kg
Aluminum	Aluminum (waste treatment) {GLO}| recycling of aluminum| Cut-off, S	4.47	kg
	Waste aluminum {CH}| treatment of sanitary landfill | Cut-off, S	0.138	kg
Plastic	Waste plastic, mixture {Europe without Switzerland} | treatment of waste plastic, mixture, municipal incineration | Cut-off, S	1.72	kg
	Waste plastic, mixture {Europe without Switzerland} | treatment of waste plastic, mixture, sanitary landfill | Cut-off, S	0.738	kg
Electronic components	Waste plastic, consumer electronics {CH}| treatment of municipal incineration | Cut-off, S	0.67	kg
	Waste plastic, consumer electronics {GLO}| treatment of waste plastic, consumer electronics, sanitary landfill, wet infiltration class (500mm) | Cut-off, S	0.33	kg
Packaging cardboard	Core board (waste treatment) {GLO}|recycling of core board| Cut-off, S	0.16	kg
	Municipal solid waste {IT}| treatment of incineration | Cut-off, S	0.013	kg
	Municipal solid waste {CH}| treatment of sanitary landfill | Cut-off, S	0.021	kg
Packaging plastics	PET (waste treatment) {GLO}| recycling of PET | Cut-off, S	0.093	kg
	Municipal solid waste {IT}| treatment of incineration | Cut-off, S	0.068	kg
	Municipal solid waste {CH}| treatment of sanitary landfill | Cut-off, S	0.131	kg
Transport from consumer to treatment plant	Municipal waste collection service by 21 metric ton lorry {GLO}| market for | Cut-off, S	1.82	tkm

Table 7- Activity mapping of SimaPro process (EOL of NGB).

5.1.2 Electric heat pump

A heat pump is a device that employs the refrigeration cycle to transfer thermal energy from the outside to heat a building (or a segment of a building). Many heat pumps can also operate in the opposite direction, cooling the building by removing heat from the enclosed space and rejecting it outside. A compressor inside the device uses electricity to increase the temperature of the heat extracted from the outside air. The heat pump can also provide cooling by transferring warm indoor air to the outside.

An electric heat pump with a nominal heat input of 10 kw was used to conduct the analysis for this study. The COP is used to determine heat pump efficiency (Coefficient of Performance). This is a measurement of the heat pump's usable heat output to the energy input required for operation. The COP normally ranges from 3 to 5. The SPF (Seasonal Performance Factor), which may be thought of as an average COP for the full heating season, is another way to gauge efficiency. This accounts for weather variables and provides a more accurate indicator of efficiency. In this study, it has been considered that heat pumps in Europe typically have COP of 4.3. The various activity data utilized for the evaluation are described in the table 8 in more detail. The primary reference database was ecoinvent v3.

Characteristic	Amount	Unit	Source
General information			
Thermal energy produced in life span	2 227.50	kW	-
Nominal heat input	10	kW	Manufacturer data
Refrigerant gases charge	2.753	kg	Conto Termico
Lifespan	2	Months	-
Surface	150	m^2	-
Energy needs	89.1	kWh / m^2 /y	-
Mass	36	Kg	-
Components (A1-A3)			
Reinforced Steel	40.79	kg	Primary data, Keman et al. 2019
Steel low-alloyed	10.87	kg	Primary data, Keman et al. 2019
Copper	12.10	kg	Primary data, Keman et al. 2019
Elastomer	5.43	kg	Primary data, Keman et al. 2019
Polyvinylchloride	0.54	kg	Primary data, Keman et al. 2019
Refrigerant gas (R134a)	2.75	kg	Famiglietti et al. 2022
Air fan	1.90	kg	ecoinvent
Electronic components	1.00	kg	Kemna et al. 2019 and Ecoinvent
Manufacturing process (A1-A3)			
Water consumption	389.16	kg	ecoinvent
Emissions of water in air	0.058	m^3	ecoinvent
Emissions of water in water	0.330	m^3	ecoinvent
Lubricating oil	2.7	kg	ecoinvent
Electricity	140	kWh	ecoinvent
Heat	136	MJ	ecoinvent
Refrigerant gas (R134a) production	0.082	kg	ecoinvent
Refrigerant gas (R134a) leakages	0.082	kg	ecoinvent
Transport input (lorry >32 metric ton, euro5)	21.62	tkm	Keman et al. 2019
Transport input (train)	50.45	tkm	Keman et al. 2019
Packaging			
Plastic film	0.32	kg	Keman et al. 2019

Polystyrene	0.16	kg	Keman et al. 2019
Corrugated board	0.32	kg	Keman et al. 2019
Distribution			
Transport from manufacturer to consumer (freight, lorry 16-32 metric ton, euro5)	36.44	tkm	Keman et al. 2019
Transport from manufacturer to consumer (freight, lorry 16-32 metric ton, euro5)	14.57	tkm	Keman et al. 2019
Transport from manufacturer to consumer (light commercial vehicle)	3.64	tkm	Keman et al. 2019
Use phase (B6)			
Electricity	518.02	kWh	-
Refrigerant gas production	0.009	kg	PEP ecopassport program
Refrigerant gas leakages	0.009	kg	PEP ecopassport program
Maintenance (B2)			
Components substitution	-	-	Keman et al. 2019
Transport to consumer	0.003	tkm	Keman et al. 2019
End of life (C2 – C4)			
Copper	97% recycling, 11.74	kg	Keman et al. 2019
	3% landfill, 0.36	kg	Keman et al. 2019
Steel	97% recycling, 50.11	kg	Keman et al. 2019
	3% landfill, 1.55	kg	Keman et al. 2019
Plastic	70% recycling, 4.18	kg	Keman et al. 2019
	30% landfill, 1.79	kg	Keman et al. 2019
Electronic components	67% recycling, 1.94	kg	Keman et al. 2019
	33% landfill, 0.95	kg	Keman et al. 2019
Packaging cardboard	83% recycling, 0.26	kg	Keman et al. 2019
	6% incineration, 0.01	kg	Keman et al. 2019
	11% landfill, 0.03	kg	Keman et al. 2019
Packaging plastics	32% recycling, 0.15	kg	Keman et al. 2019
	23% incineration, 0.11	kg	Keman et al. 2019
	44% landfill, 0.21	kg	Keman et al. 2019
Refrigerant gas (R134a)	20% vent into air, 0.55	kg	Keman et al. 2019
	80% recycling, 2.20	kg	Keman et al. 2019
Transport from consumer to treatment plant	3.64	tkm	Famiglietti et al. 2021

Table 8- Activity data and references for the EHP (LS.2m).

The system boundaries of material production include extraction of raw materials and primary components like Air fan and electronic components, transport to the manufacturing plant, production processes, and packaging. All materials are represented by a process from the ecoinvent v3 European or global market database, which includes stage A1. also, an average distance of 1000 km for transport input and 700 km plus 50 km of transportation distance from manufacturing plant to building site (consumer) were assumed for all materials and components. The ecoinvent processes which was run by SimaPro assigned to represent production to use phase of all EHP materials (A1-B7) are listed in the next table.

Activity Data	Secondary Data	Mass/ Energy	Unit
Resources: material/fuels (A1)			
Reinforced Steel	Reinforcing steel {GLO}| market for | Cut-off, S	4.08E+01	kg
Steel low-alloyed	Steel, low-alloyed {GLO}| market for | Cut-off, S	1.09E+01	kg
Copper	Copper {GLO}| market for | Cut-off, S	1.21E+01	kg
Elastomer	Tube insulation, elastomer {GLO}| market for | Cut-off, S	5.43E+00	kg
Polyvinylchloride	Polyvinylchloride, bulk polymerized {GLO}| market for | Cut-off, S	5.41E-01	kg
Refrigerant gas	Refrigerant R134a {GLO}| market for | Cut-off, S	2.75E+00	kg
Air fan	Fan, for power supply unit, desktop computer {GLO}| market for | Cut-off, S	1.90E+00	kg
Electronic components	Electronics, for control units {GLO}| market for | Cut-off, S	1.00E+00	kg
Input from Technosphere: Electricity/Heat (A2, A3, A4, B1, B2, B6)			
Electricity (mf)	Electricity, medium voltage {IT}| market for | Cut-off, S	1.40E+02	kWh
Heat	Heat, district, or industrial, natural gas {RER}| market group for | Cut-off, S	1.37E+03	MJ
refrigerant	Refrigerant R134a {GLO}| market for | Cut-off, S	0.08259	kg
Electricity (use)	Electricity, low voltage {IT}| market for | Cut-off, S	5.18E+02	kWh
Heat	Refrigerant R134a {GLO}| market for | Cut-off, S	0.009177	kg
Transport input	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	2.16E+01	tkm
	Transport, freight train {Europe without Switzerland} | market for | Cut-off, S	5.04E+01	tkm
Water Consumption	Tap water {GLO}| market group for | Cut-off, S	3.89E+09	kg
Transport from manufacturer to consumer	Transport, freight, light commercial vehicle {GLO}| market group for transport, freight, light commercial vehicle | Cut-off, S	3.64E+09	tkm
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	3.64E+09	tkm
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	1.46E+09	tkm
Transport to consumer	Transport, freight, light commercial vehicle {Europe without Switzerland} | market for transport, freight, light commercial vehicle | Cut-off, S	0.003	tkm
Lubricating oil	Lubricating oil {GLO}| market for | Cut-off, S	2.7	kg
Plastic film	Packaging film, low density polyethylene {GLO|market for |Cut-off, S	0.3215	kg
Polystyrene	Polystyrene, expandable {GLO}| market for | Cut-off, S	0.1607	kg
Corrugated board	Corrugated board box {RER}| production | Cut-off, S	0.3215	kg

Table 9- Activity mapping of SimaPro process (production phase of EHP).

The End Of Life (EOL) stage was modelled so that burdens and benefits of recycling, landfill and incineration were analysed through this stage. This provides a clearer view on how they contribute to the total impact. The system boundaries for EOL stage (C1-C4) for the EHP system include transportation from consumer to treatment plant (50 km), treatment of the materials and disposal of residual inert material. Once treated at the sorting plant, waste materials can either go to landfill, incineration, or recycling/reuse facility. There is a degree of uncertainty introduced when using the recyclability rate of construction materials. Data on this is scarce and there is always a level of uncertainty depending on the data source itself. ecoinvent processes used to simulate the end-of-life stages of NGB system is presented in the subsequent table.

Activity Data	**Secondary Data**	**Mass/ Energy**	**Unit**
Waste treatment (C2 – C4)			
Copper	Scrap copper {Europe without Switzerland} | market for scrap copper | Cut-off, S	11.74	kg
	Scrap steel {Europe without Switzerland} | treatment of scrap steel, inert material landfill | Cut-off, S	0.36	kg
Steel	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S	50.11	kg
	Scrap steel {Row}| treatment of inert material landfill | Cut-off, S	1.55	kg
Plastic	Waste plastic, mixture {CH}| treatment of municipal incineration | Cut-off, S	4.18	kg
	Waste plastic, mixture {Row}| treatment of waste plastic, mixture, sanitary landfill | Cut-off, S	1.79	kg
Electronic components	Waste plastic, consumer electronics {CH}| treatment of municipal incineration | Cut-off, S	1.94	kg
	Waste plastic, consumer electronics {GLO}| treatment of waste plastic, consumer electronics, sanitary landfill, wet infiltration class (500mm) | Cut-off, S	0.95	kg
Packaging cardboard	Waste plaster-cardboard sandwich {CH}|treatment of recycling | Cut-off, S	0.26	kg
	Waste paperboard {CH}| treatment of municipal incineration | Cut-off, S	0.02	kg
	Waste paperboard {Row}| treatment of sanitary landfill | Cut-off, S	0.03	kg
Packaging plastics	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Cut-off, S	0.15	kg
	Waste plastic, mixture {CH}| treatment of municipal incineration | Cut-off, S	0.11	kg
	Waste plastic, mixture {CH}| treatment of sanitary landfill | Cut-off, S	0.21	kg
Refrigerant gas	Used refrigerant R134a {GLO}| treatment of used refrigerant R134a, venting | Cut-off, S	0.55	kg
	Used refrigerant R134a {GLO}| treatment of used refrigerant R134a, final disposal | Cut-off, S	2.20	kg
Transport from consumer to treatment plant	Municipal waste collection service by 21 metric ton lorry {GLO}| market for | Cut-off, S	3.64	tkm

Table 10- Activity mapping of SimaPro process (EOL of EHP).

5.2 Scenarios

Product-Service Systems (PSS) are a specific type of Circular Business Model (CBM). PSS aim at providing customers with access to a function or service that a certain product delivers or provides, instead of selling the product. The expectations are high for PSS in enabling the transition towards a circular economy as these business models could provide environmental as well as economic gains [68]. Heating, ventilation, and air conditioning systems are frequently used in temporary buildings located on the mega events. Since their design cycles are extremely durable (with twenty years of life span) and the whole of their service life does not include during an event, they seem the suitable products for this kind of business model. In this research, to compare the environmental effects of HVAC systems with the short-time operation, two different business models are studied:

1. The ownership business model to serve the whole twenty-year lifespan.

Two different conditions are considered in this business model. At first, it is assumed that the consumer buys the product and accepts the responsibility for the end of life of the product, while in the second condition, after finishing the operation period, the consumer turns back the product to the company without any responsibility regarding the next life of the product.

2. The rental business model to service the usage of only two months (during the event).

Also, this business model, it is assumed two different situations. At first, the condition is evaluated where the consumer rents the product as a first user and turns back to the rental agency after the period of operation. Whereas, in the second condition, the user is the last one who is responsible related to the end of life of the product.

All in all, four different scenarios (SC) are defined, and a comparison was performed to detect the amount of environmental impact of each scenario and propose an efficient model based on the LCA analysis. This study aimed to answer the question of whether it is better for the environment to own or rent energy system for a temporary usage. A cradle-to-grave LCA was conducted to compare the life cycle environmental impacts of renting and owning a HVAC system for all case studies.

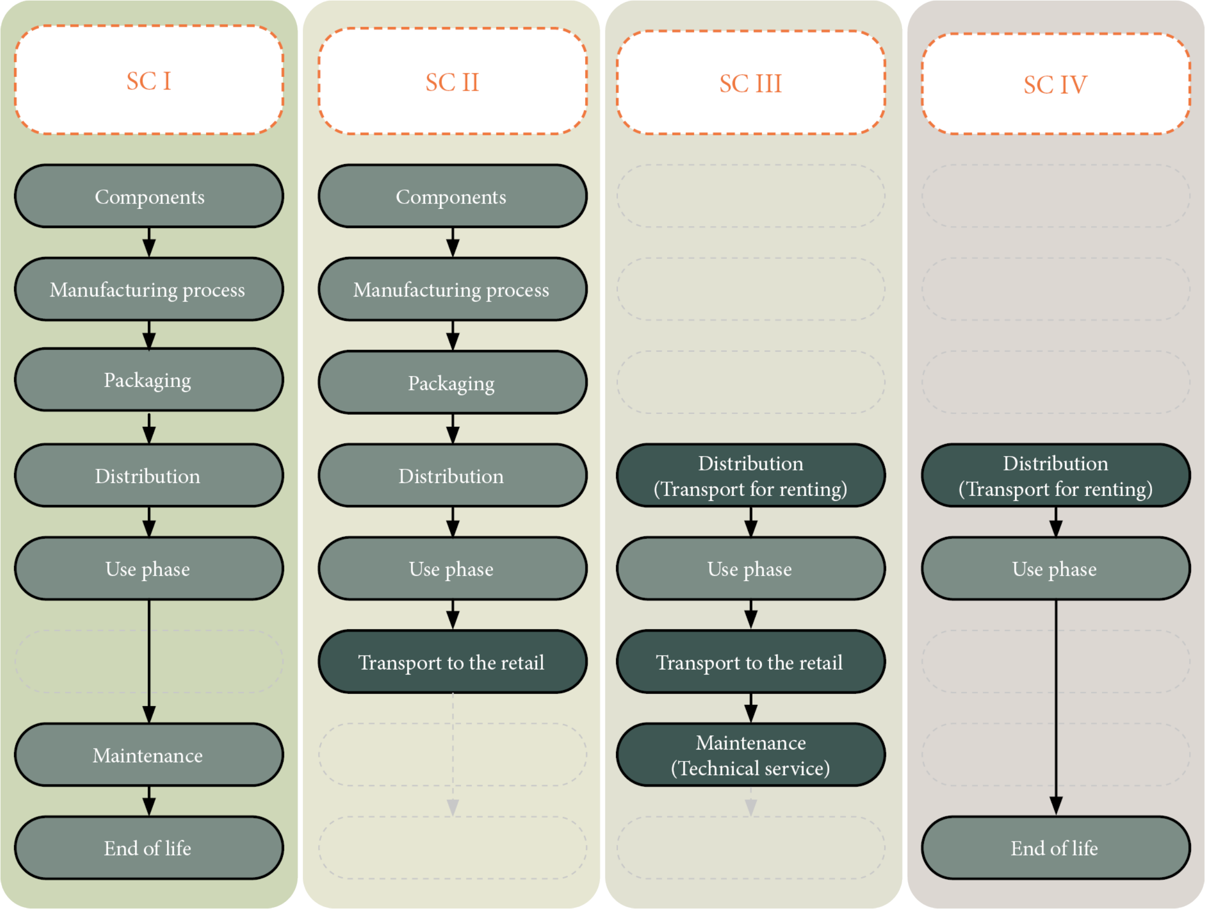


Figure 10- An overlook on the four scenarios.

5.2.1 Scenario I (Based on ownership business model)

In this business model, it is assumed that the user buys one energy system from the main company and operate until requires and then demolish it. This scenario is analysed in two different life spans for each energy system. At first an EHP and a NGB with standard life span (twenty years) and then these two systems with short life span (two months) which would be installed in mega events, were analysed. The system boundaries of this LCA are cradle to grave which include the stages of raw material extraction (A1, A2), manufacturing(A3), packaging, distribution, use (B1, B6), maintenance (B2), and end of life (C2-C4) of the selected energy system. The comprehensive use of LCA analysis has allowed for a detailed assessment of environmental effect. It could serve as a reliable baseline for subsequent study.

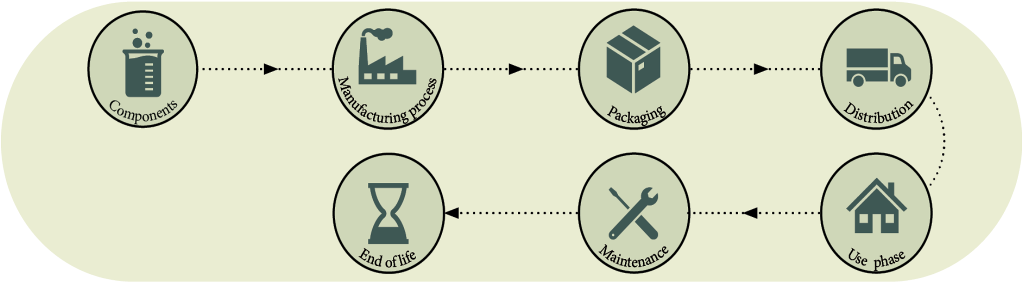


Figure 11- SC I (considered for both EHP & NGB).

5.2.2 Scenario II (Based on ownership business model)

In this business model, it is assumed that the user buys the energy system from supplier and after usage period, the product is returned to the company. In this scenario, user is not responsible about the period after usage and this stage is not considered in analysis. Same as the previous scenario, LCA is analysed in two different life spans for each energy system. The system boundaries of this LCA include the stages of raw material extraction (A1, A2), manufacturing(A3), packaging, distribution, and use (B1, B6) of the selected energy system. as shown in below diagram, the final transportation to the retail centre is also included. This scenario assumes that the user would return the product to the corporation after using it, hence the last phase of the system boundary is not considered. As a result, the user is not responsible for the product's end of life, and the company is required to repair any damages and supply the products for a second life. The figure below shows all the scenario's strengths, weaknesses, opportunities, and threats. It is notable that an extra transport to the retail should be considered. Thus, an average of 500 km for transportation distance from user to the company was assumed for one particular HVAC system.

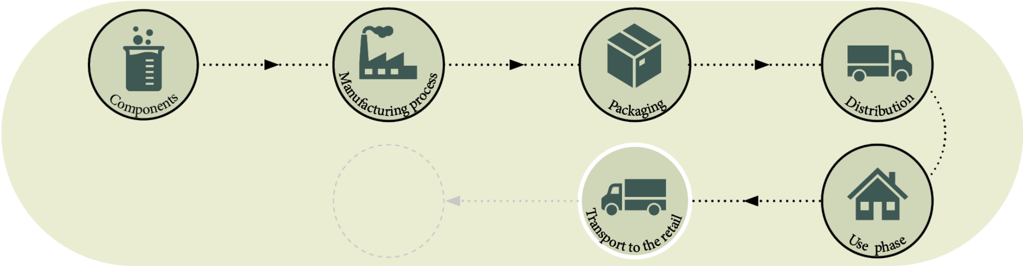


Figure 12- SC II (considered for both EHP and NGB).

5.2.3 Scenario III (Based on rental business model)

In this business model, it is assumed that the user rents the energy system from supplier and after usage period, the product is returned to the company. It means, customers can rent an HVAC system either one-time or on a subscription basis that in this study the only one time is considered.

In this scenario, company should have technical maintenance before and after each period of usage. In this occasion, analysis focus on the use phase and probable transformation. The system boundaries of this LCA are B1, B2, B6 which include the use phase and maintenance of the selected energy system.

As shown in below diagram, the intermediate and final transportations from agency to the user and after usage from customer to the agency are also included which is the average of 500 km for transportation distance (for each time) from rental agency to the user and from user to the rental agency after short time- use (1000 km in total) was assumed for one particular HVAC system.

Figure 13- SC III (considered for both EHP and NGB).

5.2.4 Scenario IV (Based on rental business model)

In the final business model, the user assumed the last one who rents the device from supplier and after usage period, the product will go for disposal. Although it is expected that the condition for the last user is not fair, but to compare with other scenarios, a technical maintenance is assumed after each time of usage. Then, the conditions are the same as the others. This analysis focus on the use phase and end of life of product which includes B1, B6 and (C2-C4).

As shown in below diagram, the intermediate transportations from agency to the consumer is calculated as an extra transportation process. Thus, an average of 500 km for transportation distance from rental agency to the last user was assumed for one particular HVAC system.

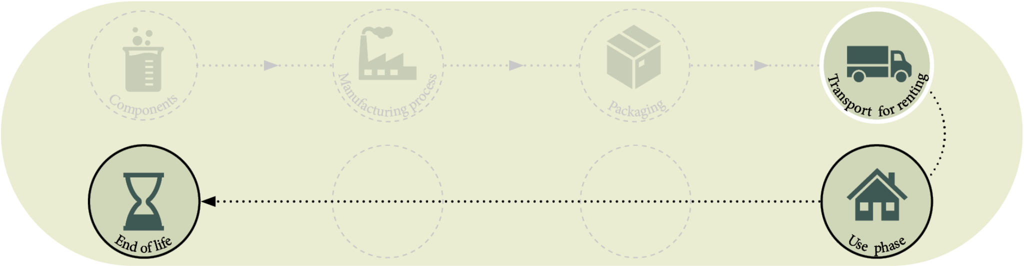


Figure 14- SC IV (considered for both EHP and NGB).

6 Analysis and results

This chapter will explain and analyze the Life Cycle Impact Assessment (LCIA) methodology and outcomes. This stream of work for characterization, normalization, and weighting scores for different kind of HVAC system (EHP & NGB), compared and studied for each life cycle stage and over the entire life cycle. The potential recommendation based on the circular economy were presented considering the result of these analysis. At first, the electric heat pump and natural gas boiler were completely modeled on SimaPro separately, considering the twenty- years- life span. In the next step, they were simulated with a 2-months of life span for temporary operation. Then, each of introduced scenario in previous chapter was modeled by SimaPro and their results were compared to introduce the best and worth case. Finally, a holistic comparison between two systems, considering the environmental impact are presented.

6.1 Life cycle impact assessment information

The Life Cycle Impact Assessment (LCIA) is the stage of an LCA analysis when the potential magnitude of a product's environmental impacts is analyzed. The processes to achieve this stage are category definition, classification, characterization, and valuation/weighting. Normalization and weighting are optional additional procedures to support in data analysis and a broad perspective. The life cycle impact assessment involves as a first element the definition of the impact categories to be considered [70]. This is a follow-up of the decisions made in the goal and scoping phase. Based on the type of information collected in the inventory phase the boundaries defined in the goal and scoping may be redefined. The impact categories considered are:

- Abiotic resources
- Biotic resources
- Land use
- Global warming
- Stratospheric ozone depletion
- Ecotoxicological impacts
- Human toxicological impacts
- Photochemical oxidant formation
- Acidification
- Eutrophication
- Work environment

The life cycle impact assessment includes as a second element classification of the inventory input and output data [69]. Classification is a qualitative step based on scientific analysis of relevant environmental processes. The classification must assign the inventory input and output data to potential environmental impacts i.e., impact categories. The LCIA method used in this research is EN 15804+ A2 Method V1.03 / EF 3.0 normalization and weighting set.

The life cycle impact assessment includes, as a third element, characterization of the inventory data [70]. The characterization is to model categories in terms of indicators, and, if possible, to provide a basis for the aggregation of the inventory input and output within the category. This is also done in terms of the indicator to represent an overall change or loading to that category. The result of characterization is that the combination of category indicators represents initial loading and resource depletion profile. It essentially translates the LCI results (per FU) into common units for each impact category and then sums the results together.

All Sixteen impact categories studied in this research (in the succeeding figure) are in accordance with EN 15804. Since the weight of two impact categories of climate change and Resource use, minerals, and metals prevailed over the rest of the categories, the focus of this research put on these two impact categories.

The previous element, characterization, results in a quantitative statement on different impact categories e.g., global warming, stratospheric ozone depletion and ecotoxicological effects. Comparison of these categories is not immediately possible. Therefore, the life cycle impact assessment includes as a fourth element a valuation/ weighting of the impact categories against each other [70]. Weighting aims to rank, weight, or, possible, aggregate the results of different life cycle impact assessment categories to arrive at the relative importance of these different results. The weighting process is not technical, scientific, or objective as these various life cycle impact assessment results e.g., indicators for greenhouse gases or resource depletion, are not directly comparable. However, weighting may be assisted by applying scientifically based analytical techniques [70].

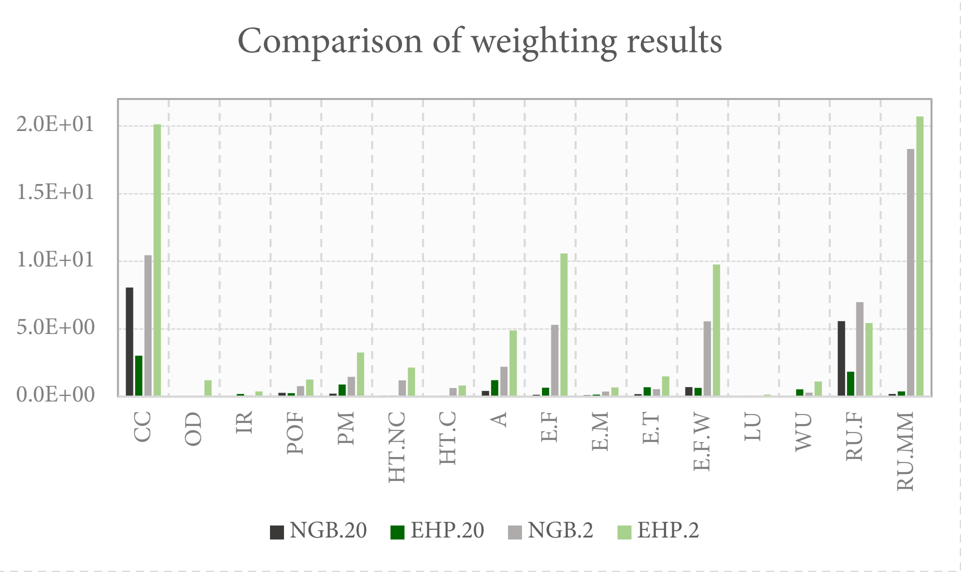


Figure 15- Comparison of weighting results (between NGB and EHP).

In the following, there is the table of characterization, normalization and weighting factors used in this LCA for two systems with both life span of twenty years and two months considering the first scenario.

Impact category	**Abb.**	**Unit**	**Characterisation (FU)**				**Weighting (μPt)**			
			NGB		EHP		NGB		EHP	
			2.M	20.Y	2.M	20.Y	2.M	20.Y	2.M	20.Y
Climate change	CC	kg CO_2eq	4E-01	3E-01	8E-01	1E-01	1E+01	8E+00	2E+01	3E+00
Ozone depletion	OD	kg CFC11 eq	4E-08	3E-08	1E-06	2E-08	4E-02	4E-02	1E+00	3E-02
Ionising radiation	IR	kBq U-235 eq	8E-03	2E-03	3E-02	2E-02	9E-02	2E-02	4E-01	2E-01
Photochemical ozone formation	POF	kg NMVOC eq	7E-04	2E-04	1E-03	2E-04	8E-01	3E-01	1E+00	3E-01
Particulate matter	PM	disease inc.	1E-08	1E-09	2E-08	6E-09	1E+00	2E-01	3E+00	9E-01
Human toxicity, non-cancer	HTNC	CTUh	1E-08	8E-10	3E-08	1E-09	1E+00	6E-02	2E+00	8E-02
Human toxicity, cancer	HTC	CTUh	5E-10	3E-11	7E-10	4E-11	6E-01	4E-02	8E-01	6E-02
Acidification	A	mol H+ eq	2E-03	4E-04	4E-03	1E-03	2E+00	4E-01	5E+00	1E+00
Eutrophication, freshwater	EF	kg P eq	3E-04	8E-06	6E-04	4E-05	5E+00	1E-01	1E+01	7E-01
Eutrophication, marine	EM	kg N eq	2E-04	7E-05	4E-04	1E-04	4E-01	1E-01	7E-01	1E-01
Eutrophication, terrestrial	ET	mol N eq	3E-03	9E-04	7E-03	3E-03	6E-01	2E-01	2E+00	7E-01
Ecotoxicity, freshwater	EFW	CTUe	1E+01	2E+00	2E+01	1E+00	6E+00	7E-01	1E+01	6E-01
Land use	LU	Pt	6E-01	2E-01	1E+00	6E-01	6E-02	1E-02	1E-01	5E-02
Water use	WU	m3 depriv.	4E-02	5E-03	2E-01	7E-02	3E-01	4E-02	1E+00	5E-01
Resource use, fossils	RUF	MJ	5E+00	4E+00	4E+00	1E+00	7E+00	6E+00	5E+00	2E+00
Resource use, minerals, and metals	RUMM	kg Sb eq	2E-05	2E-07	2E-05	3E-07	2E+01	2E-01	2E+01	4E-01

Table 11- Characterization and weighting factor of NGB and EHP.

6.2 **Life cycle assessment results** (Scenarios for both case studies)

In this chapter, due to the importance of two main impact category of Climate Change (CC) and Resource Use, Minerals, and Metals (RUMM), the life cycle stages and the contribution to each of these categories for both NGB & EHP are analysed. The results of characterization and normalization for both systems with life span of two months (in all scenarios) are presented in the following.
While the characterization results related to the twenty years of life span for both case studies can be found in the Appendix I & II.

6.2.1 Characterization results (Scenario I)

- NGB

According to the performed analysis for NGB, it is obvious that the use phase (A1) dominates in the climate change category, Because the most of emissions from combustion release in this phase. Logically, due to the electronics for control units (54%) and copper (34%) in A1 stage and brazing solder (100%) in A3 stage, the components and manufacturing process have the critical role in the resource use, minerals, and metals category.

Scenario I (NGB I LS 2.M)

Impact category	Unit	Total	A1-A4				B1, B2, B6		C2 - C4
			Comp.	MfP.	Dist.	Pack.	Use.	Main.	EOL
CC	kg CO_2eq	4E-01	7E-02	2E-02	3E-03	5E-04	3E-01	1E-06	4E-03
RUMM	kg Sb eq	2E-05	9E-06	7E-06	1E-08	3E-10	3E-08	5E-12	8E-10

Table 12- Results of two impact categories for all phases of NGB.

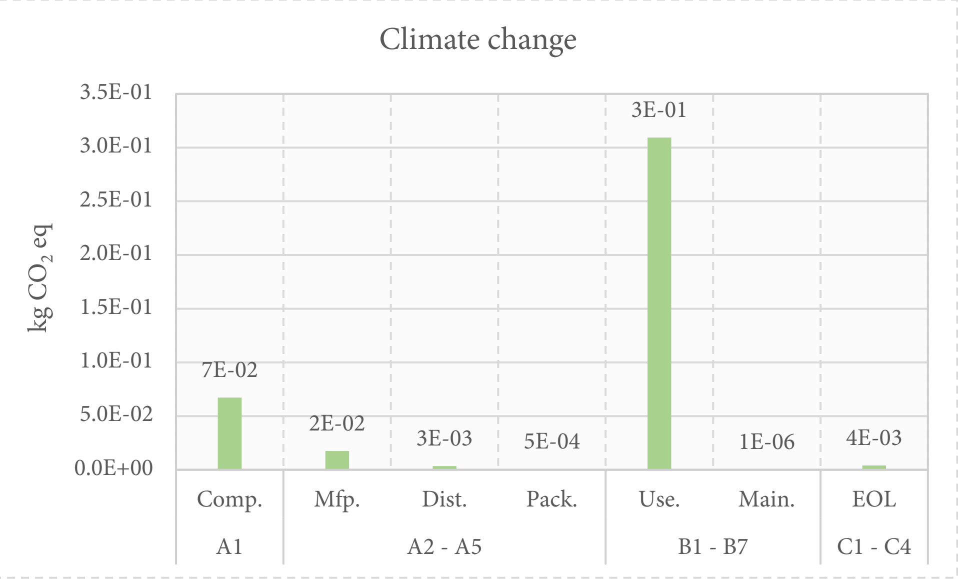


Figure 16- Characterization results of SC. I (NGB I LS 2.m).

The contributions of each phase were carefully examined in order to identify the most effective component. It is shown in diagram below, the most portion of Use phase is dedicated to the emissions with a ratio of 76%. These emissions include the emission to the air / water during the combustion of natural gas in boiler. The emissions induced by combustion could increase due to lack of optimum setting or certain controls (e.g., dampers).

There are several strategies for improving the combustion process and the overall performance of a boiler like: maximize the combustion efficiency, observation on the CO_2 emissions, steam outlet conditions, flue gas outlet (stack) temperature and NO_x emissions. In the next section, related suggestions to improve the efficiency of system and decrease the environmental impacts will be proposed.

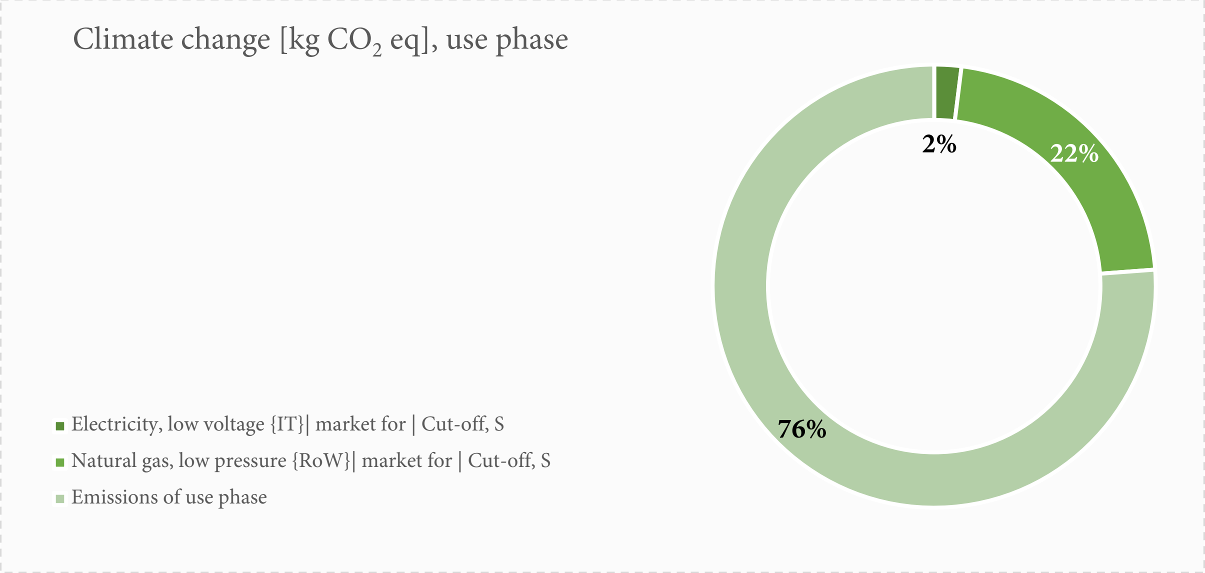


Figure 17- Climate change, use phase, (NGB I LS 2.m).

The next figure illustrates that the most effective stage after use phase is assigned to the components with a ratio of 17% in impact category of climate change. It means that the sort of utilized metals and components and the extraction of row material has a relatively notable impact on the value of CO_2eq emissions [kg CO_2eq] in production phase of energy building systems.

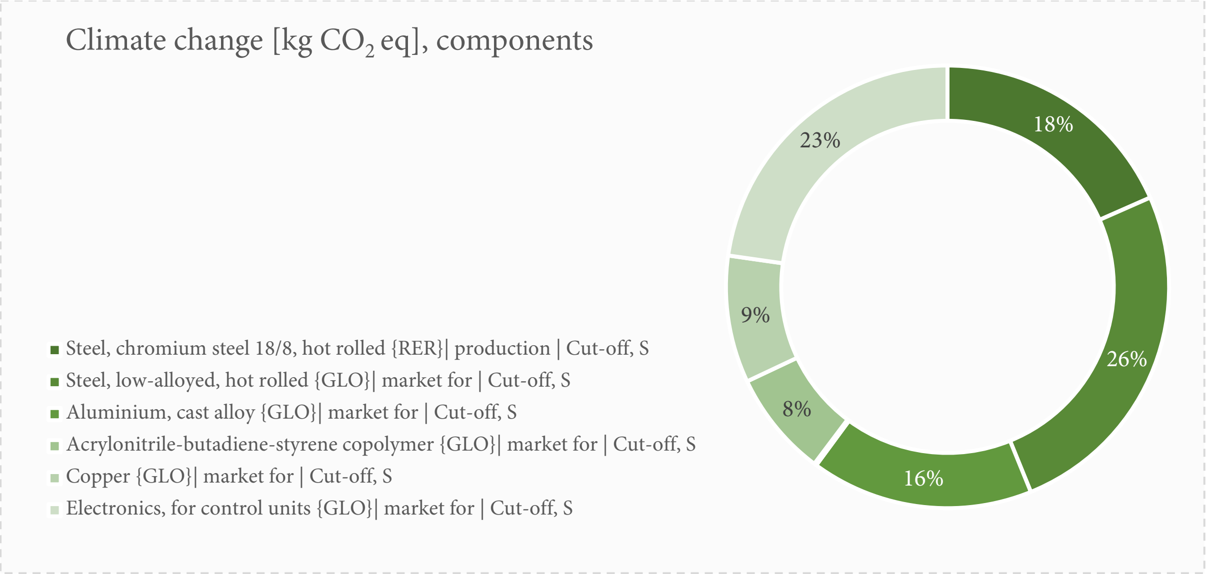


Figure 18- Climate change, components, (NGB I LS 2.m).

The following Figure depicts that in the second studied impact category, components with a ratio of 55% and manufacturing process with a portion of 45% play a significant role in the variation of resource use, minerals, and metals [kg Sb eq].

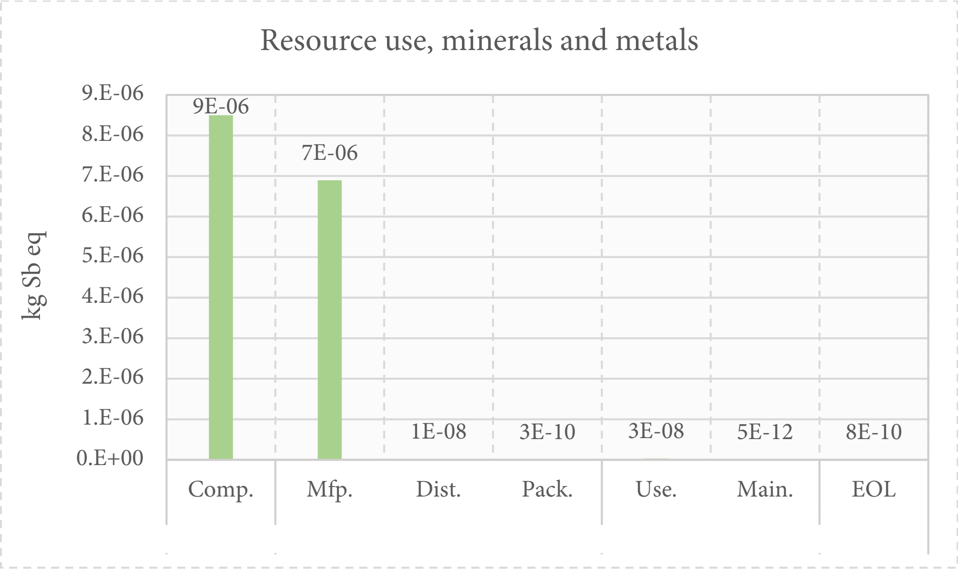


Figure 19- Characterization results of SC. I (NGB I LS 2.m).

With a detailed look, it would be clear that the portion of electronic components (54%) and copper (34%) significantly dominants the rest.

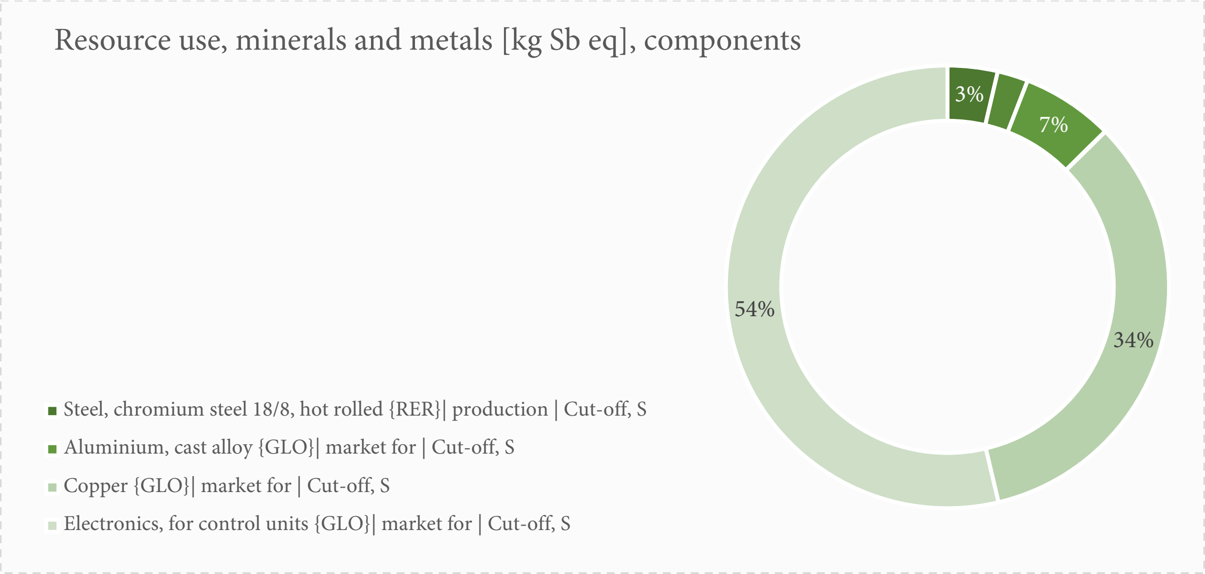


Figure 20- Resource use, minerals and metals, components, (NGB I LS 2.m).

In addition, according to the next figure, in the manufacturing process, brazing solder with a ratio of 46% and electricity consumption with medium voltage with 26% have the most significant contribution in CO_2eq emissions.

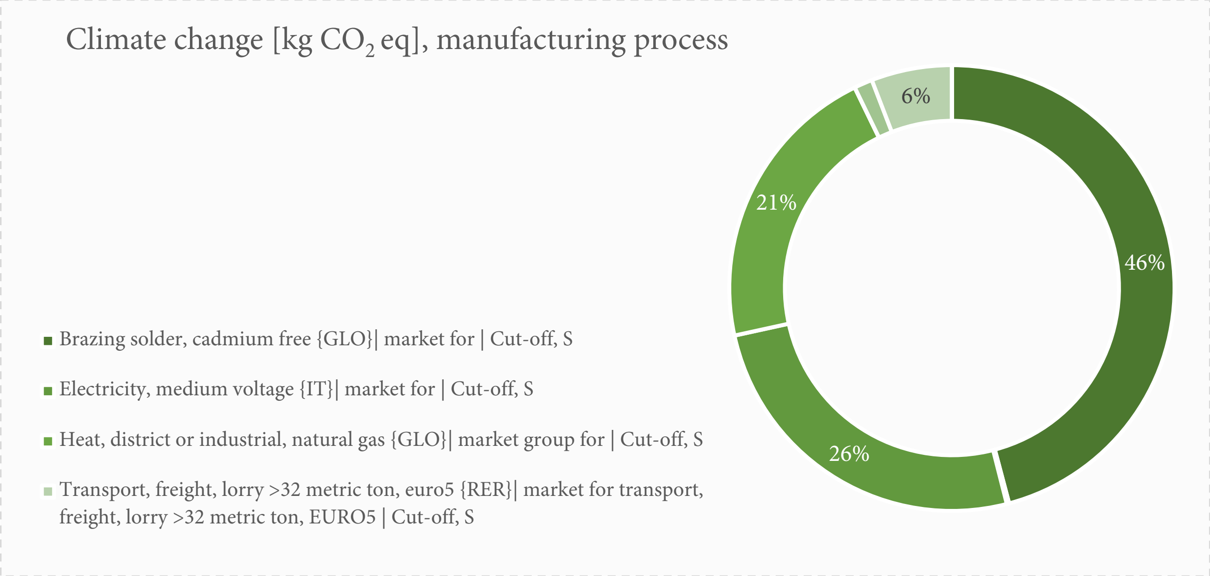


Figure 21- Climate change, manufacturing process, (NGB I LS 2.m).

- EHP

This is while the EHP's highest ratio of CO_2eq of the climate change category is allocated to the end-of-life phase (C1-C4) with a ratio of 51%. Components, manufacturing process and use phase with portions of 17%, 16% and 15% consequently, are placed in the next places.

Scenario I (EHP I LS 2.M)									
Impact category	Unit	Total	A1-A4				B1, B2, B6		C2 - C4
			Comp.	Mfp.	Dist.	Pack.	Use.	Main.	EOL
CC	kg CO_2eq	8E-01	1E-01	1E-01	7E-03	8E-04	1E-01	3E-06	4E-01
RUMM	kg Sb eq	2E-05	2E-05	3E-08	2E-08	5E-10	2E-07	1E-11	4E-09

Table 13- Results of two impact categories of SC. I (EHP I LS 2.m).

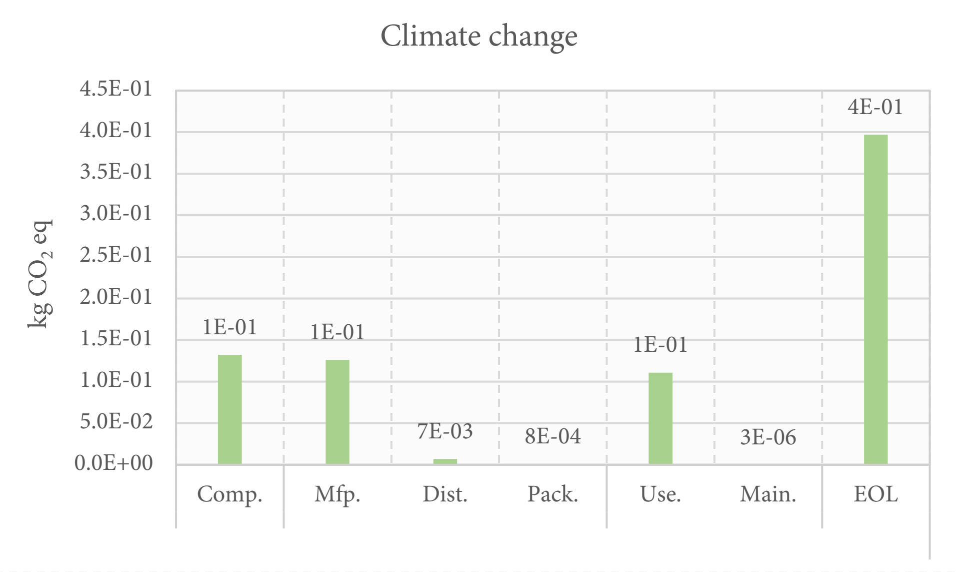


Figure 22- Characterization results of SC. I (EHP I LS 2.m).

Having performed a detailed study, it was figured out that the main reason behind the assigning the maximum portion of CO_2eq emissions to the end-of-life stage, is the venting of refrigerants emitting in this phase. Regarding the investigation in other important stages, refrigerant clearly has the highest impact compared to other substance. It indicates that setting up specific regulations and strategies to regulate emissions resulting from refrigerant consumption and the selection of low-emitting refrigerants might be highly advantageous in reducing the amount of CO_2eq. emitted into the atmosphere.

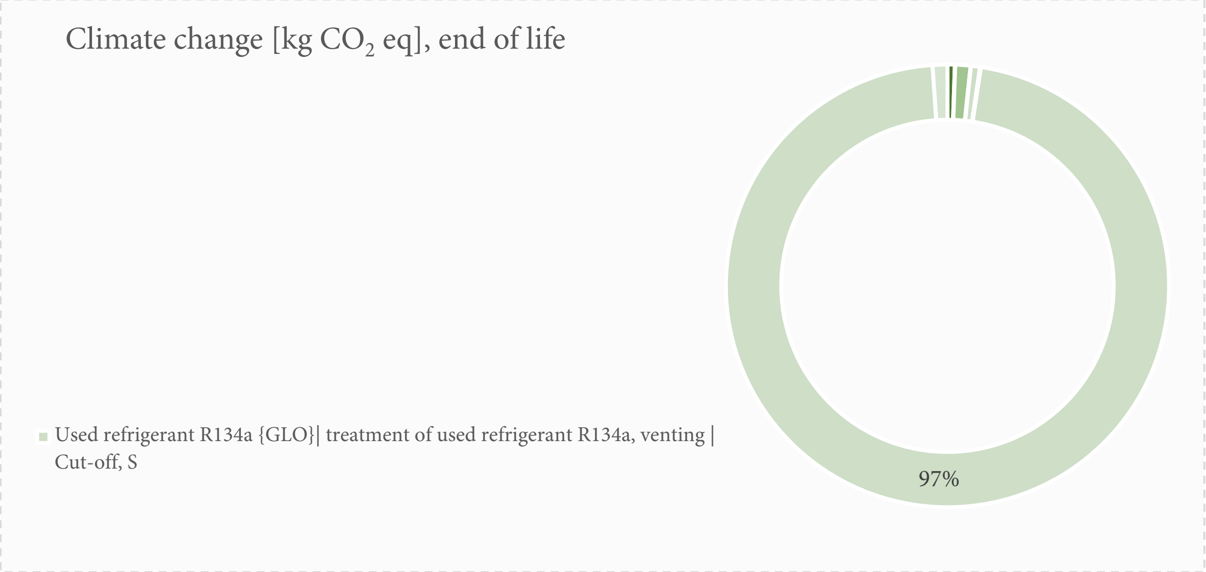


Figure 23- Climate change, end of life, (EHP I LS 2.m).

The graphic below demonstrates that components with a ratio of 99% have a considerable influence on resource consumption, minerals, and metals [kg Sb eq.], like NGB.

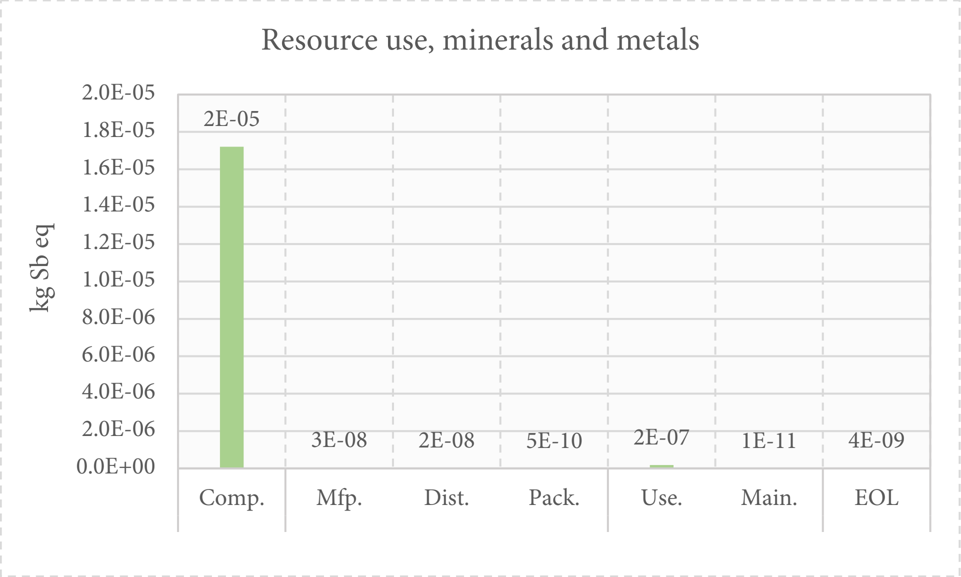


Figure 24- Characterization results of SC. I (EHP I LS 2.m).

Next diagram shows that copper receives the majority of contributions, with a ratio of 57%. Electronics, with a share of 27%, is in second place with a comparatively big disparity.

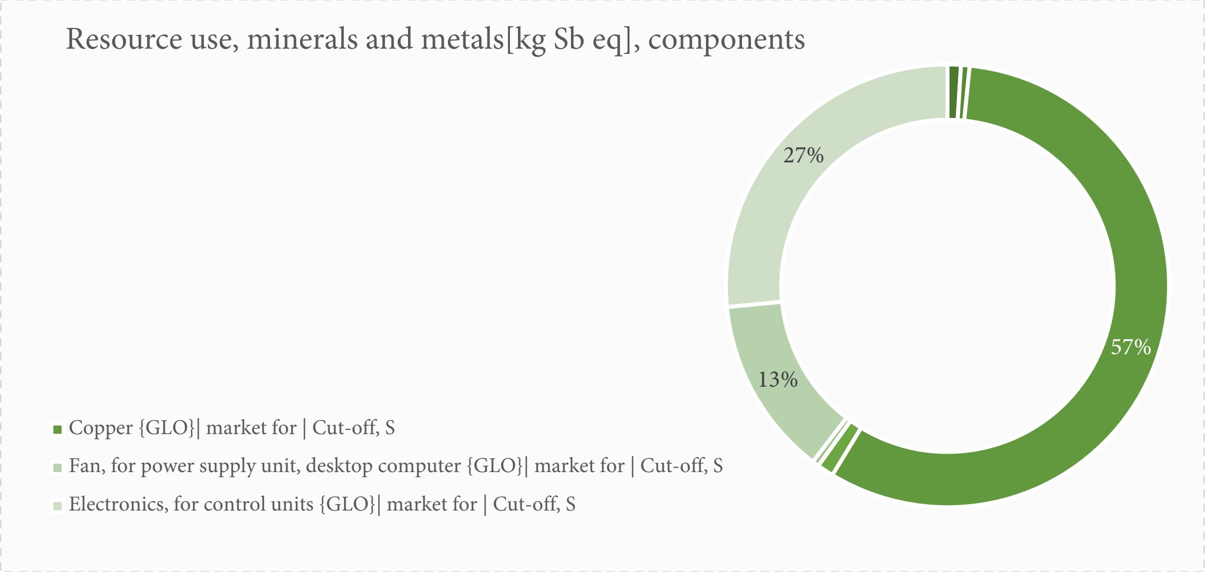
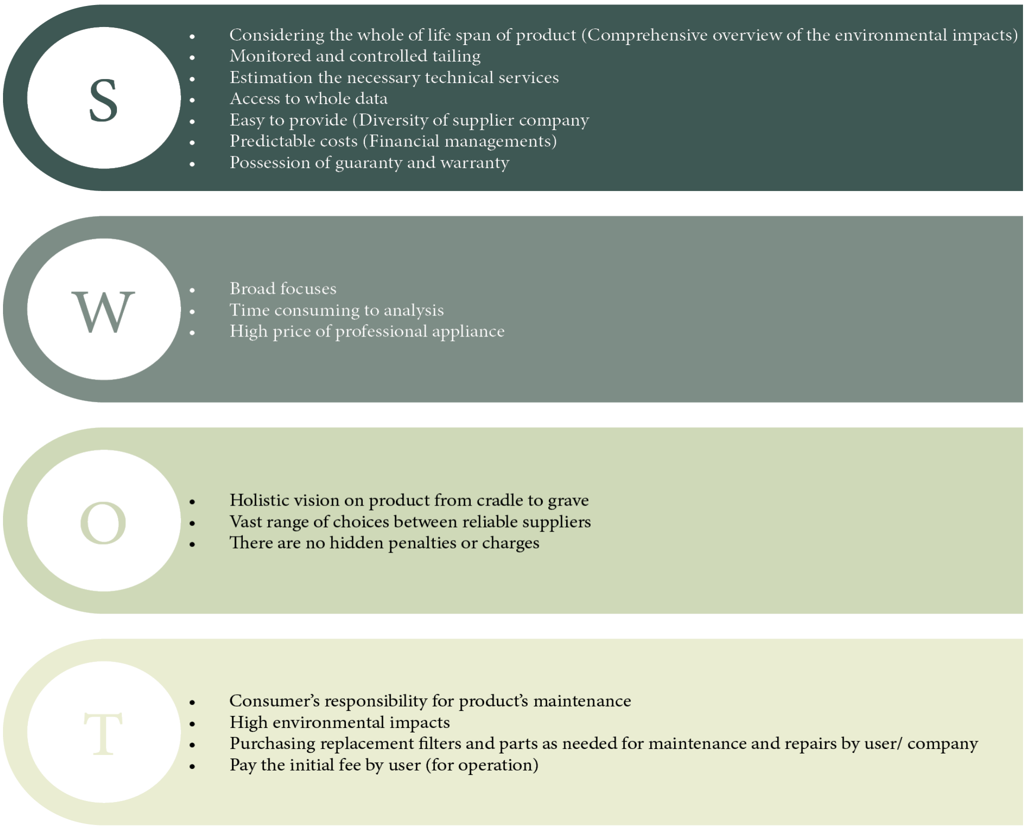


Figure 25- Resource use, minerals and metals, components, (EHP I LS 2.m).

Overall, the strength and weaknesses of this scenario would be apparent when considering the whole life span for both case studies in scenario I. In this SC, the consumer is required to buy the product for a limited period of use, which is not cost-effective. On the other side, the product is manufactured to last for 20 years, and if it were to be stored after use or destroyed, it would degrade and have a significant detrimental effect on the environment. The SWOT diagram below shows all of features of this story.



- Considering the whole of life span of product (Comprehensive overview of the environmental impacts)
- Monitored and controlled tailing
- Estimation the necessary technical services
- Access to whole data
- Easy to provide (Diversity of supplier company
- Predictable costs (Financial managements)
- Possession of guaranty and warranty

- Broad focuses
- Time consuming to analysis
- High price of professional appliance

- Holistic vision on product from cradle to grave
- Vast range of choices between reliable suppliers
- There are no hidden penalties or charges

- Consumer's responsibility for product's maintenance
- High environmental impacts
- Purchasing replacement filters and parts as needed for maintenance and repairs by user/ company
- Pay the initial fee by user (for operation)

Figure 26- SWOT diagram (SC I).

6.2.2 Characterization results (Scenario II)

- NGB

Since it was defined in the previous chapter, it is assumed in the second scenario that the consumer purchases the HVAC system with no idea of how it would be managed after its expected lifetime has ended. It is based on the ownership business model. Therefore, LCIA was thus conducted in this scenario only until the end of the use phase.

It is evident that, in accordance with the study carried out for NGB scenario II, the outcomes reflect those of the first scenario. It means the use phase in the climate change impact category and component and manufacturing process of resource use, mineral and metal, are the most effective stages in comparison with the rests.

Scenario II (NGB I LS 2.M)

Impact category	Unit	Total	A1- A4				B1, B6
			Comp.	Mfp.	Dist.	Pack.	Use.
CC	kg CO_2 eq	4E-01	7E-02	2E-02	2E-02	5E-04	3E-01
RUMM	kg Sb eq	2E-05	9E-06	7E-06	6E-08	3E-10	3E-08

Table 14- Results of two impact categories of SC. II (NGB II LS 2.m).

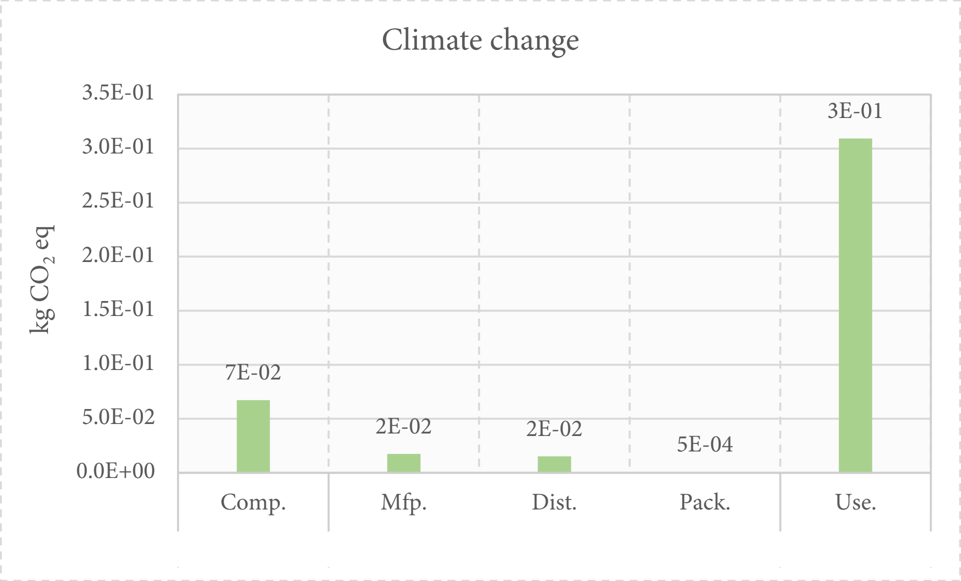


Figure 27- Characterization results of SC. II (NGB II LS 2.m).

In the scenario II, diagram of climate change and diagram of Resource use, minerals and metals [kg Sb eq], for component stage and use phase are excatly similar to the scenario I, so they are neglected for a better illustration.

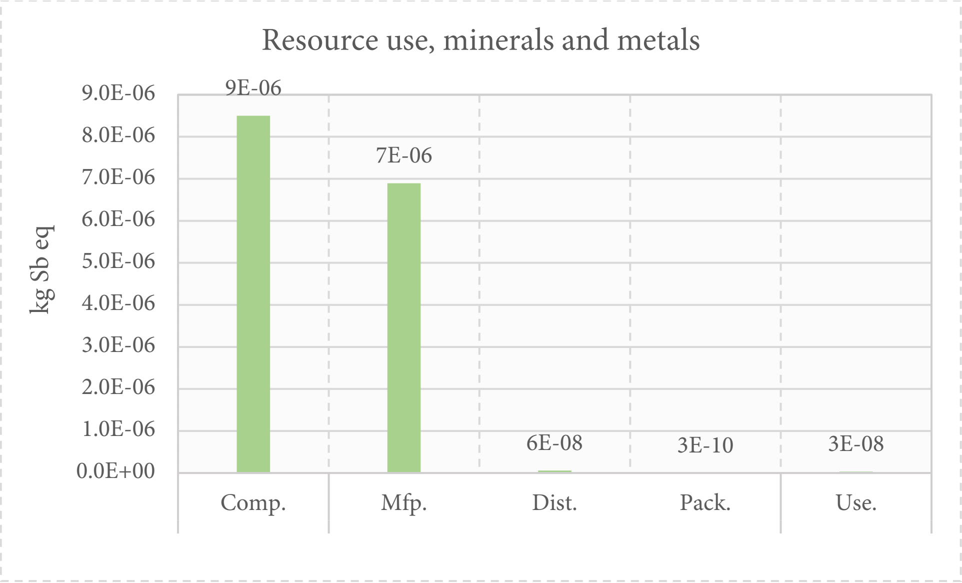


Figure 28- Characterization results of SC. II (NGB II LS 2.m).

- EHP

In this scenario, for EHP, the highest portion of climate change [CO_2eq] is dedicated to the component, manufacturing process and use phase with ratios of 33%, 31% and 27% subsequently.

Scenario II (EHP I LS 2.M)

Impact category	Unit	Total	A1- A4				B1, B6
			Comp.	Mfp.	Dist.	Pack.	Use.
CC	kg CO_2 eq	4.0E-01	1.3E-01	1.2E-01	3.7E-02	8.4E-04	1.1E-01
RUMM	kg Sb eq	1.7E-05	1.7E-05	3.3E-08	1.4E-07	4.9E-10	1.8E-07

Table 15- Results of two impact categories of SC. II (EHP II LS 2.m).

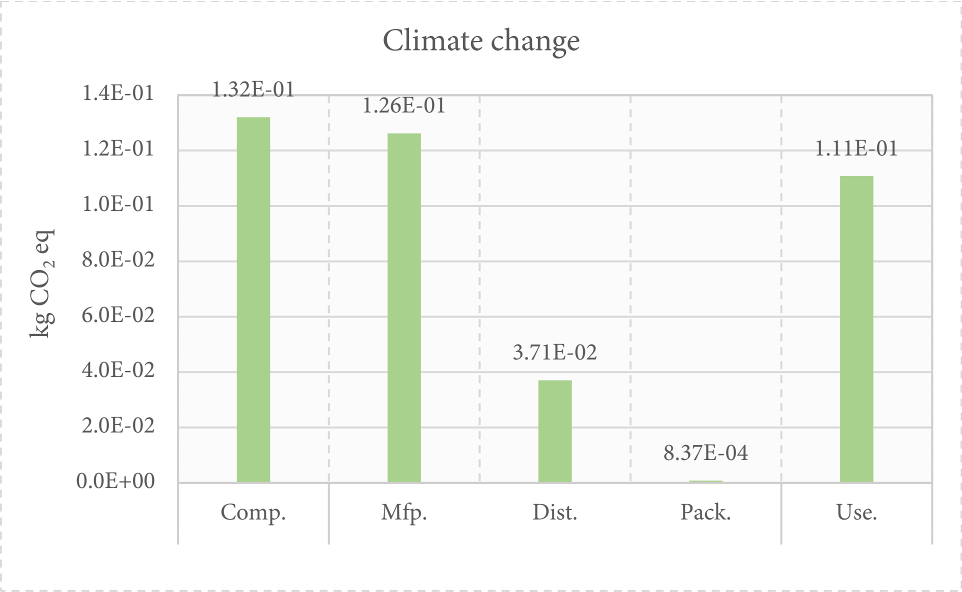


Figure 29- Characterization results of SC. II (EHP II LS 2.m).

Only 6% of the use phase is constituted of leakage; the majority (94%) of this phase is devoted to low voltage electricity consumption. It is interesting to note that these leaks are caused by refrigerant emissions.

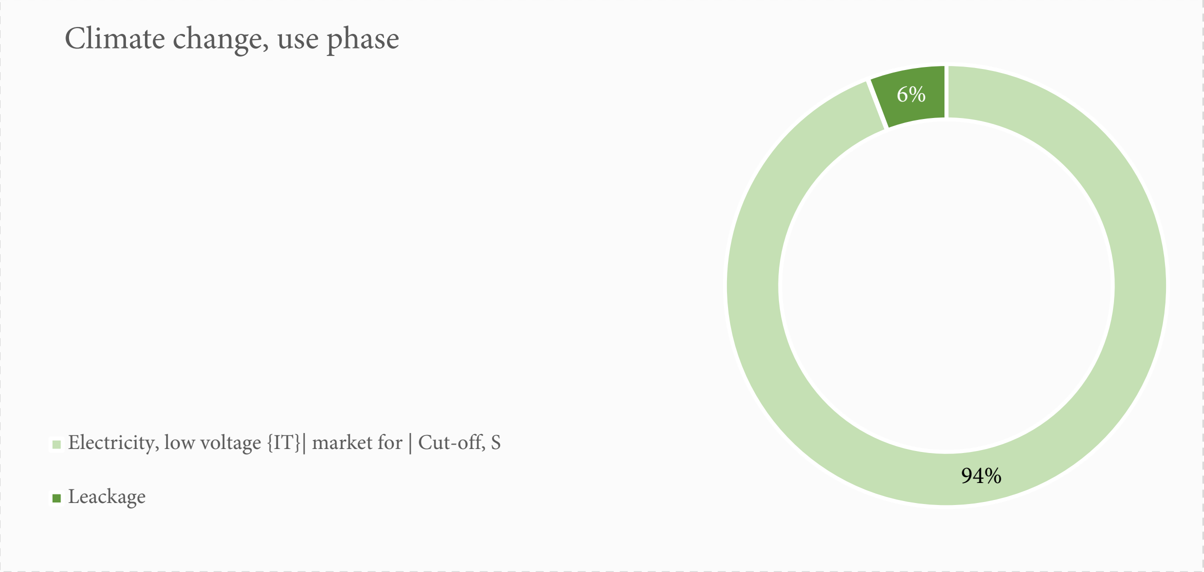


Figure 30- Climate change, use phase, (EHP II LS 2.m).

A deeper look at the accompanying pie chart reveals that emissions from the manufacturing process are mostly caused through the use of refrigerants, with a peak ratio of 46%. Likewise, the locations of the heat derived from natural gas and electricity demand, which have respective ratios of 28% and 23%, are ranked second.

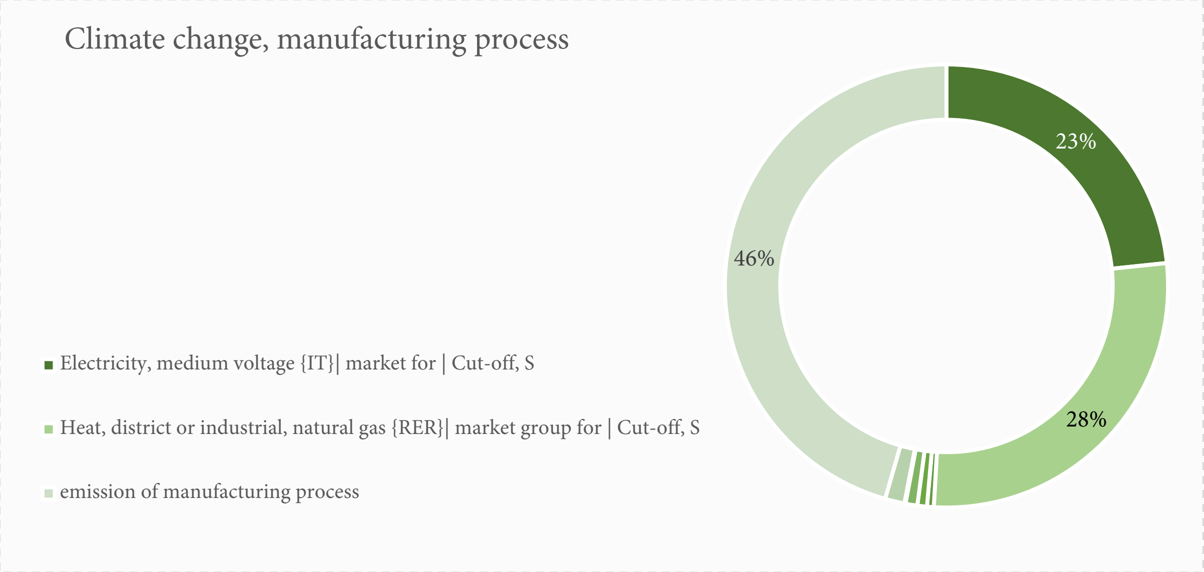


Figure 31- Climate change, manufacturing process, (EHP II LS 2.m).

However, the resource use diagram for minerals and metals [kg Sb eq] at the component stage in scenario II is identical to that in scenario I, therefore it is skipped for better demonstration.

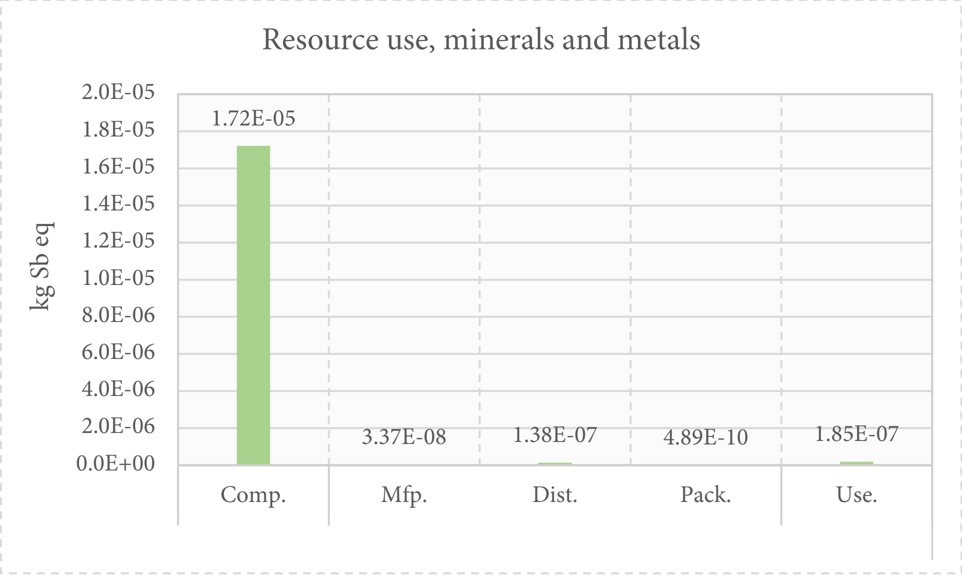


Figure 32- Characterization results of SC. II (EHP II LS 2.m).

In this SC, the consumer is required to buy the product and turn back to the company after usage. It is more economical rather than previous SC due to the possibility of returning a significant portion of initial cost of purchasing the product to the user. Prediction of second life of system is out of this study but what is clear it is with a correct management; the environmental impact can reduce significantly in comparison with the previous scenario. The SWOT diagram below shows all of features of this SC.

- The possibility of monitored and controlled tailing
- Estimation the necessary technical services
- Easy to provide (Diversity of supplier company
- Predictable costs (Financial managements)
- Possession of guaranty and warranty

- Unknown process after usage
- Weak control on the whole process
- Continuity, supply chain
- Risk of missing products categories with high waste phase impact due to cradle to use phase analysis
- Being responsible for all servicing of your HVAC equipment and any required repairs over time

- No responsibility about the end of life of product.
- There are no hidden penalties or charges
- Flexible to transfer the ownership plan to the new owner

- Environmental effects
- Purchasing replacement filters and parts as needed for maintenance and repairs by user/ company
- Pay the initial fee by user (for operation)

Figure 33- SWOT diagram (SC II).

6.2.3 Characterization results (Scenario III)

- NGB

The third scenario is established based on the rental business model for the situation when the user rents the product from a rental agency for a fixed timeframe. After usage, the product must be returned to the company by the customer. In this case, simply the period of usage was considered at, and the user is regarded as the first user of the circular pattern.

As anticipated, the use phase accounts for the vast majority of CO_2eq emissions under the category of climate change impacts, with a ratio of 91%.

Scenario III (NGB I LS 2.M)

Impact category	Unit	Total	B1, B2, B6		EXT. Stage
			Use.	Main.	Dist.
CC	kg CO_2eq	3E-01	3E-01	1E-06	3E-02
RUMM	kg Sb eq	1E-07	3E-08	5E-12	1E-07

Table 16- Results of two impact categories of SC. III (NGB III LS 2.m).

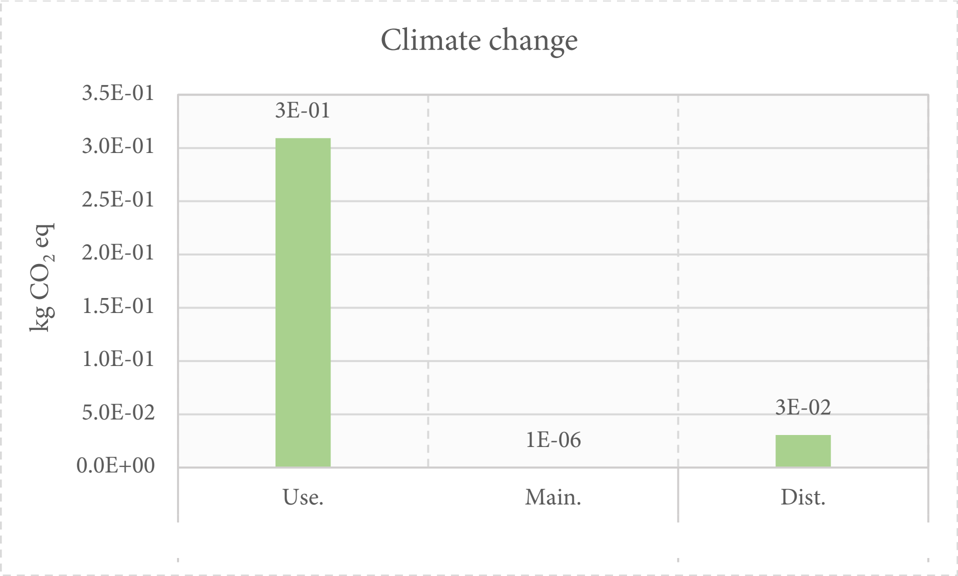


Figure 34- Characterization results of SC. III (NGB III LS 2.m).

In the scenario III, diagram of "climate change, use phase" and "Resource use, minerals and metals, use phase" are excatly similar to the scenario I, so they are neglected for a better illustration.

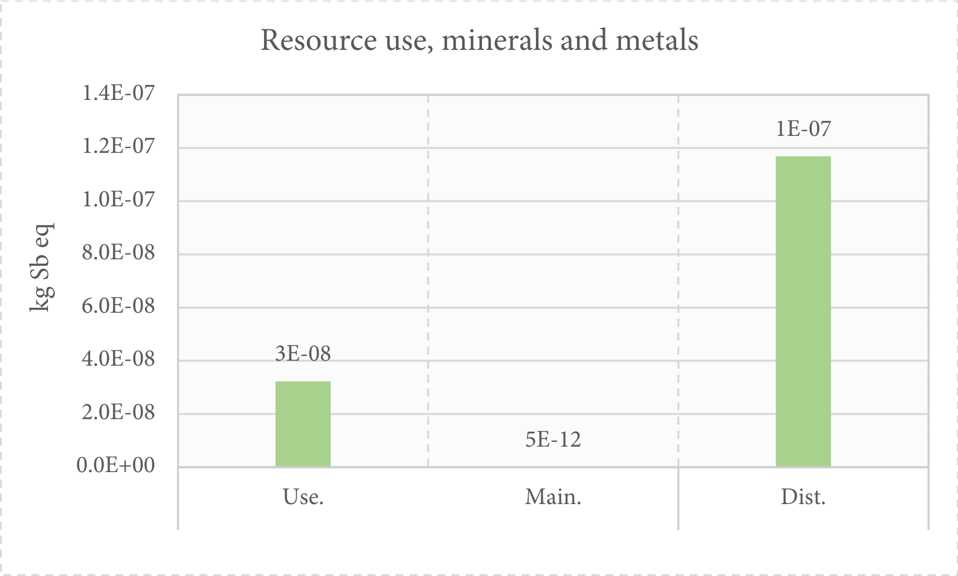


Figure 35- Characterization results of SC. III (NGB III LS 2.m).

- EHP

Moreover, the use phase obtains 64% of the contributions in the third EHP scenario, which is the largest proportion. Due to the stage's similarity to the one preceding, a detailed representation is excluded. However, it is crucial to remember that electricity consumption constitutes 94% of the use phase.

Scenario III (EHP I LS 2.M)

Impact category	Unit	Total	B1, B2, B6		EXT. Stage
			Use.	Main.	Dist.
CC	kg CO_2eq	1.7E-01	1.1E-01	2.5E-06	6.1E-02
RUMM	kg Sb eq	4.1E-07	1.8E-07	9.6E-12	2.3E-07

Table 17- Results of two impact categories of SC. III (EHP III LS 2.m).

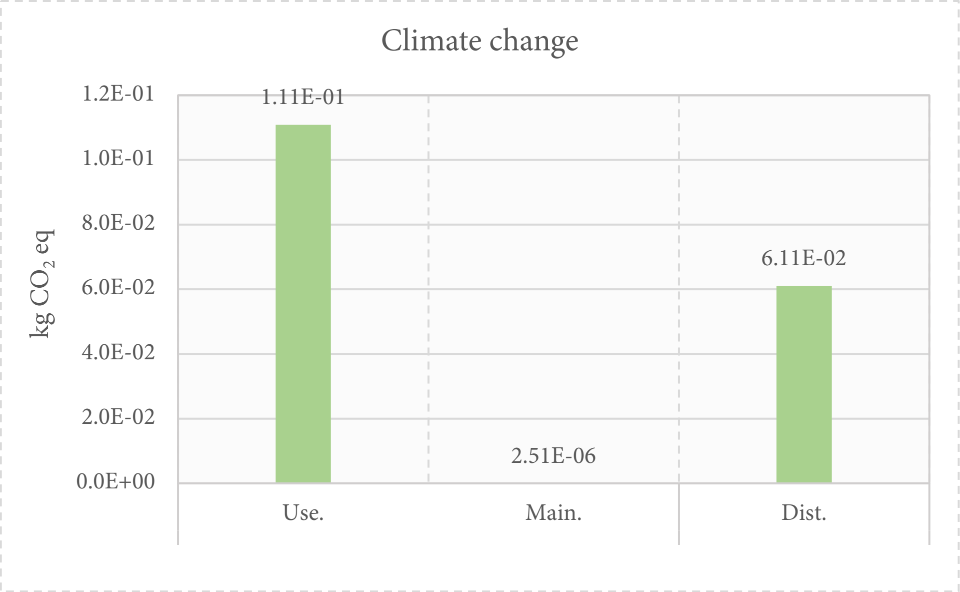


Figure 36- Characterization results of SC. III (EHP III LS 2.m).

In the scenario III, diagram of "climate change, use phase, (EHP III LS 2.m)" and is excatly similar to the scenario II. Also regarding "Resource use, minerals and metals, use phase" the diagram was neglected since the factor "Electricity, low voltage" had a ratio of 100%.

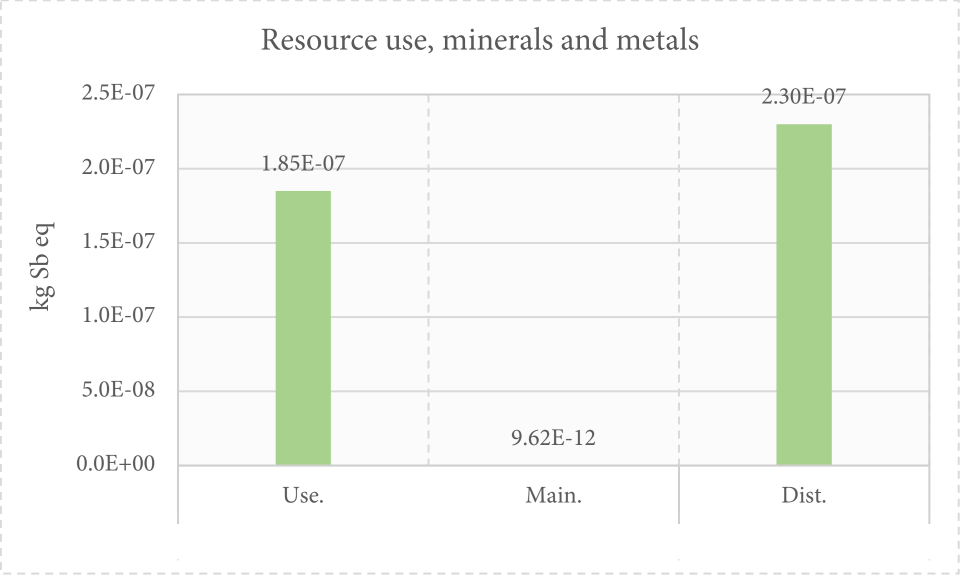


Figure 37- Characterization results of SC. III (EHP III LS 2.m).

Based on the rental business model, the expenses in this situation are substantially lower, but the customer is still obligated to pay the penalty in the case that the product is likely to be damaged. The rental circular economy encourages a particular sustainability-centered strategy that seeks to strengthen a long-term focus on responsible consumer product consumption and cutting-edge method of transport, logistics, and procurement.

S

- Competitive advantages
- No initial large cash outlay to buy
- Less analysis due to the Focus on user phase
- Market development
- Decrease environmental pollutions
- Easy access to the suitable services

W

- Weak control on the whole process
- Continuity, supply chain
- Reliability to different users
- Risk of missing products categories with high waste phase & initial phases impact due to use phase analysis
- Not calculating the environmental impact arising from cradle to gate process
- Risk of imprecise LCA results due to analysis of specific profiles
- Weak Control of user sector's consumption and material flows

O

- New jobs (as a rental agent)
- Power of selection of available policies (depends on the top management)
- No worries about repair and replacements (maintenance)
- Save money for initial costs
- Get the Right System for Your Needs
- HVAC renters are responsible for all maintenance and emergencies.
- No responsibility for user after usage (free decision)

T

- Increasing Transportation damages
- Variable price of transportation
- Availability of shipping company
- Lack of safety (more movement)
- Limitation in regional cooperation
- Location, geographical limitations
- Responsibility in maintenance
- Market demand
- Royalty to the rental regulations
- New contracts and partners
- Obstacles to be faced (available user, technical revisions, accessibility, etc.)
- Lack of control of private consumption
- User acceptance in terms of both purchase intention and frequent activation after purchase
- Pay the penalty in case of damage to the device
- Finding reputable supplier
- Depreciation due to different usage

Figure 38- SWOT diagram (SC III).

6.2.4 Characterization results (Scenario. IV)

For the circumstance when the user hires the product from a rental agency for a short duration of time, the fourth scenario is implemented based on the rental business model (like scenario III). The distinction between this scenario and the previous one is that the present user was regarded as this loop's last user. It implies that the final user picks up the rental equipment from the leasing agency and disposes of it after use. Therefore, in this case, the evaluation phase spans from its transportation from the manufacturer to the consumer to the product's end of life.

- NGB

Scenario IV (NGB I LS 2.M)					
Impact category	Unit	Total	EXT. Stage	B1, B2, B6	C2 - C4
			Dist.	Use.	EOL
CC	kg CO_2eq	3E-01	2E-02	3E-01	4E-03
RUMM	kg Sb eq	9E-08	6E-08	3E-08	8E-10

Table 18- Results of two impact categories of SC. IV (NGB IV LS 2.m).

With a ratio of 94%, the use phase is as predicted situated at the top position of contributions.

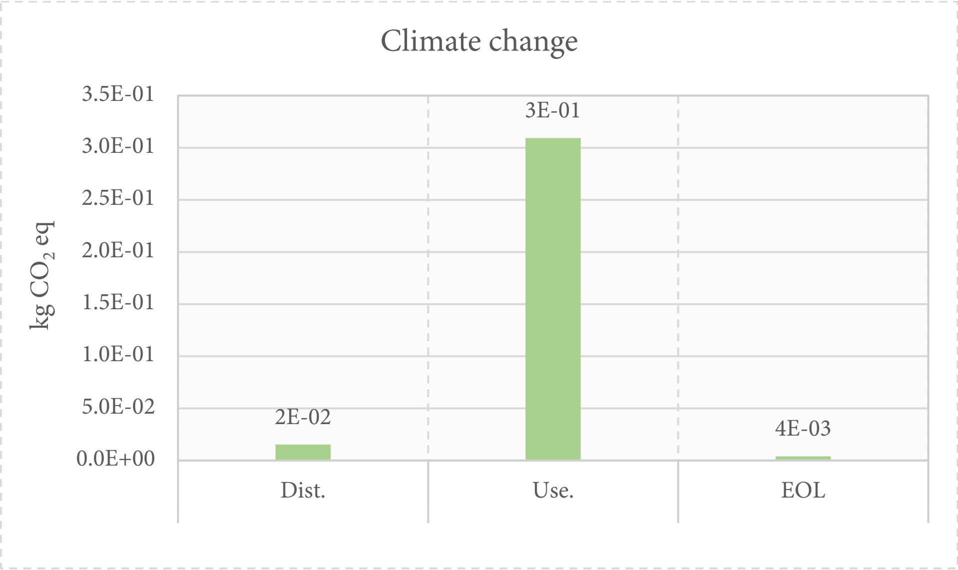


Figure 39- Characterization results of SC. IV (NGB IV LS 2.m).

In the scenario IV, diagram of “climate change” and diagram of “resource use, minerals and metals [kg Sb eq], components” are repetitively similar to their counterparts in scenario I and scenario II, so they are neglected for a better illuestration.

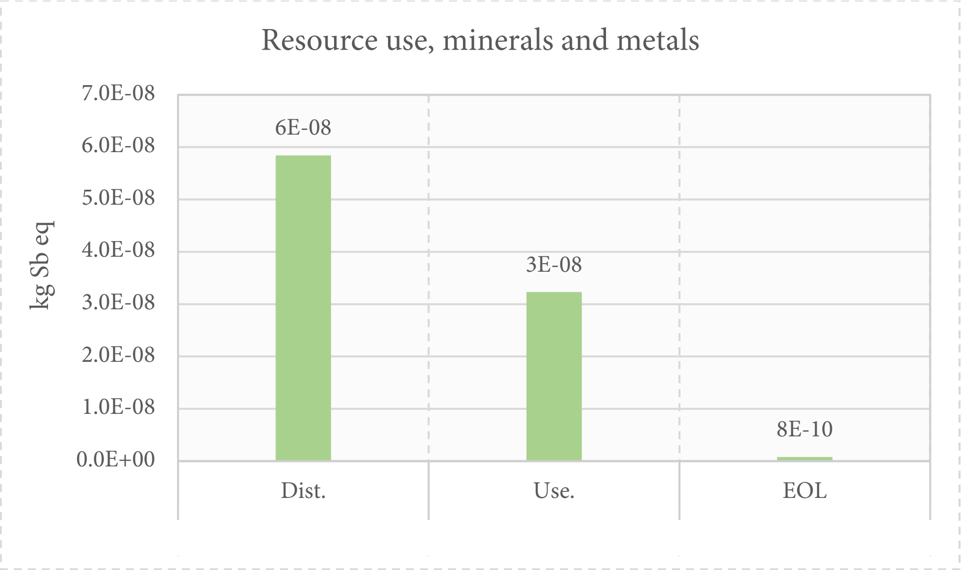


Figure 40- Characterization results of SC. IV (NGB IV LS 2.m).

By including the "end of life" stage to the analyses, we observe that this phase receives the majority of the allocation (74%), whereas the use phase received simply 21%.

- EHP

Scenario IV (EHP I LS 2.M)

Impact category	Unit	Total	EXT. Stage	B1, B2, B6	C2 - C4
			Dist.	Use.	EOL
CC	kg CO_2eq	5.3E-01	3.0E-02	1.1E-01	3.9E-01
RUMM	kg Sb eq	3.0E-07	1.1E-07	1.8E-07	3.6E-09

Table 19- Results of two impact categories of SC. IV (EHP IV LS 2.m).

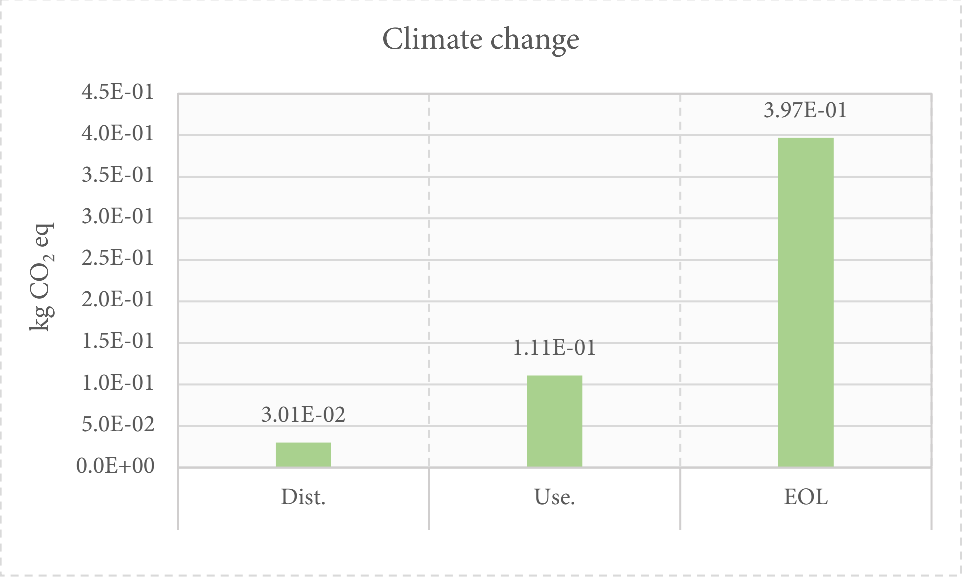


Figure 41- Characterization results of SC. IV (EHP IV LS 2.m).

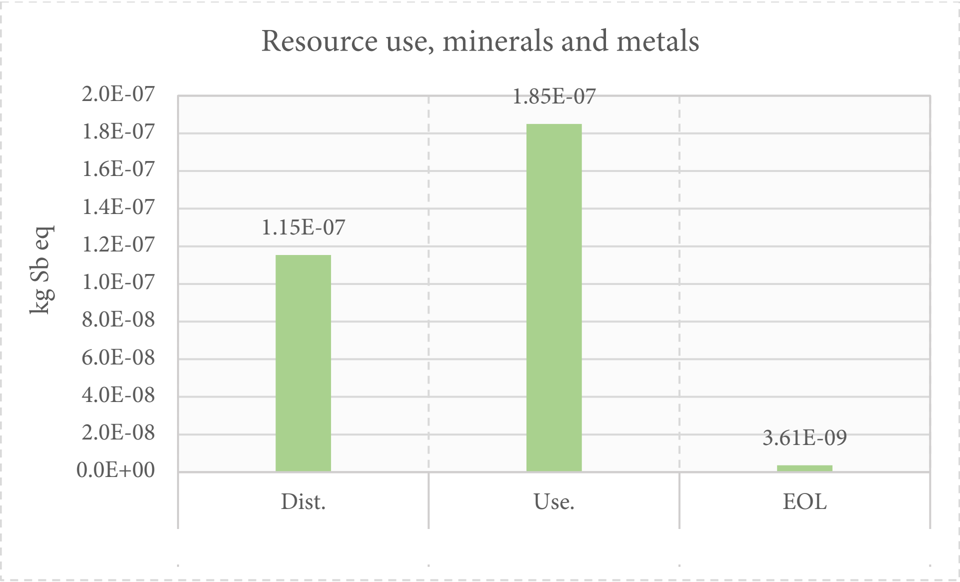


Figure 42- Characterization results of SC. IV (EHP IV LS 2.m).

In the scenario IV, diagram of “climate change,end of life” and diagram of “climate change,use phase” are repetitively similar to their counterparts in scenario I and scenario II, so they are neglected for a better illustration. In this scenario, like the previous one, thanks to the rental business model, the huge initial cost is omitted. Although there is not any guarantee about the technical issues of the product companies are responsible for products to give a technical revision on the system after each period of usage. The SWOT diagram below shows all of features of this SC.

- No initial large cash outlay to buy
- Less analysis due to the Focus on user phase
- Market development
- Decrease environmental pollutions
- Easy access to the suitable services

- Weak control on the whole process
- Continuity, supply chain
- Reliability to different users
- Risk of missing products categories with high initial phases impact due to use phase analysis
- Risk of imprecise LCA results due to analysis of specific profiles
- Weak Control of user sector’s consumption and material flows

- New jobs (as a rental agent)
- No worries about repair and replacements (maintenance)
- Save money for initial costs
- Get the Right System for Your Needs
- HVAC renters are responsible for all maintenance and emergencies.
- No responsibility for user after usage (free decision)

- Increasing Transportation damages
- Variable price of transportation
- Availability of shipping company
- Availability of storage (in case of necessity)
- Lack of safety (more movement)
- Limitation in regional cooperation
- Location, geographical limitations
- Responsibility in maintenance
- Market demand
- New contracts and partners
- Finding reputable supplier
- Depreciation due to different usage

Figure 43- SWOT diagram (SC IV).

6.2.5 Comparison of case studies (considering all scenarios)

This section included comparisons between all case studies (NGB & EHP) over their life cycles and the results of the life cycle impact assessment (including all defined scenarios). Results were explained per functional unit.

General trends:

1. Related to the EHP, Refrigerants and electricity consumption have the most variation under the impact category of climate change. This is due to the large number of emissions to the atmosphere during the end of life and even production phase.
2. Related to the NGB, natural gas emissions were known as the most effective variation under the impact category of climate change.
3. Row materials and components play a significant role in variation of resource use, mineral and metals impact category for both case studies.

Otherwise, below is presented a detailed view of the comparison between NGB & EHP:

Overall, because the use phase, which is a common phase in all scenarios, is where the majority of CO_2 eq. emissions are released the quantity of climate change [CO_2eq] is almost equal for all of scenarios. While, after the comparison between case studies with different life spans, it can be shown that the quantity of climate change [CO_2eq] in a longer life span is significantly smaller than other one.

This is the same for EHP, while the value of CO_2eq for longer life span is smaller than the shorter one. It is worthy to know, the total impact of EHP under the impact category of climate change is considerably less than NGB.

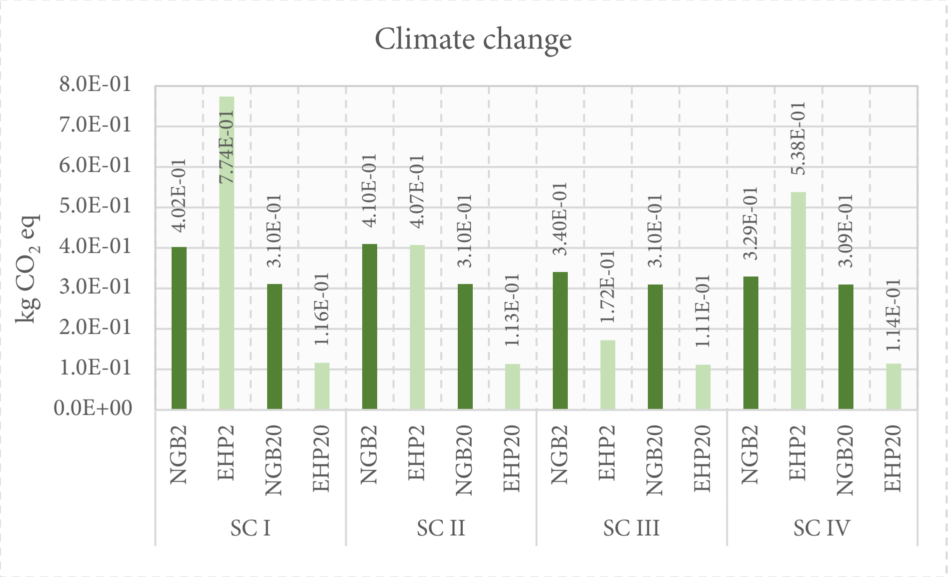


Figure 44- Climate change comparison, NGB and EHP, all scenarios.

Additionally, compared to those with longer life spans in the same scenarios, scenario I and scenario II's resource usage (kg Sb eq.) for minerals and metals is relatively significant. Since it is not reasonable to consume resources in a short period of time and to flow them to the environment and final waste disposal facilities. It should be noted that this number for scenarios III and IV is insignificant because the majority of mineral and metal use is associated to the production phase of components and materials. In the comparison between NGB and EHP it would be clear that the impact of these two systems under the impact category of resource use, mineral and metal is almost similar.

The similar analysis was carried out for EHP with different life spans (2months, 20 years) to compare the results. It is worthy to note that due to the higher electricity consumption and longer life span and consequently more refrigerant emissions and waste of materials the value of CO_2eq. emissions for longer life span is considerably smaller than the other one.

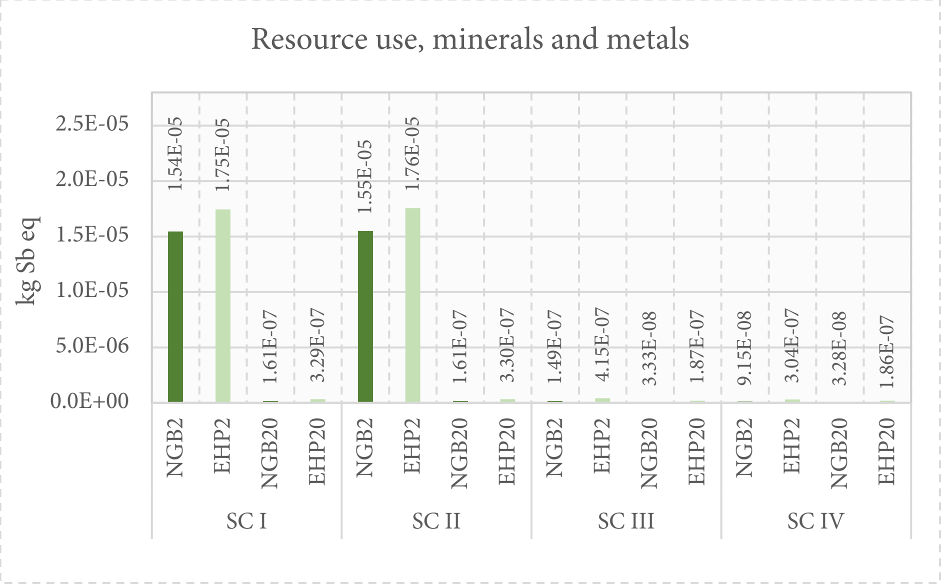


Figure 45- Resource use, minerals and metals, comparison, NGB and EHP, all scenarios.

Overall, the following diagram illustrates a comprehensive comparison between both case studies in all scenarios taking into account the normalized values (unitless) for the intended impact categories (CC and RUMM.

Upon normalization, the first thing to notice is the large effect EHP and NGB with a two-month life span have on RUMM effects of scenarios I and II. During the early stages, a large number of metals (steel, copper...) were used, which resulted from mining and component production. While this value considerably decreases for scenarios III and IV due to the removal of the production phase from the analysis. In addition, the value of CC for case studies with two- month life span is significantly more than twenty- years situation. While for all scenarios the variation of CC is relatively similar, because the most part contributed to the amount of CC, is the use phase which is present in all scenarios.

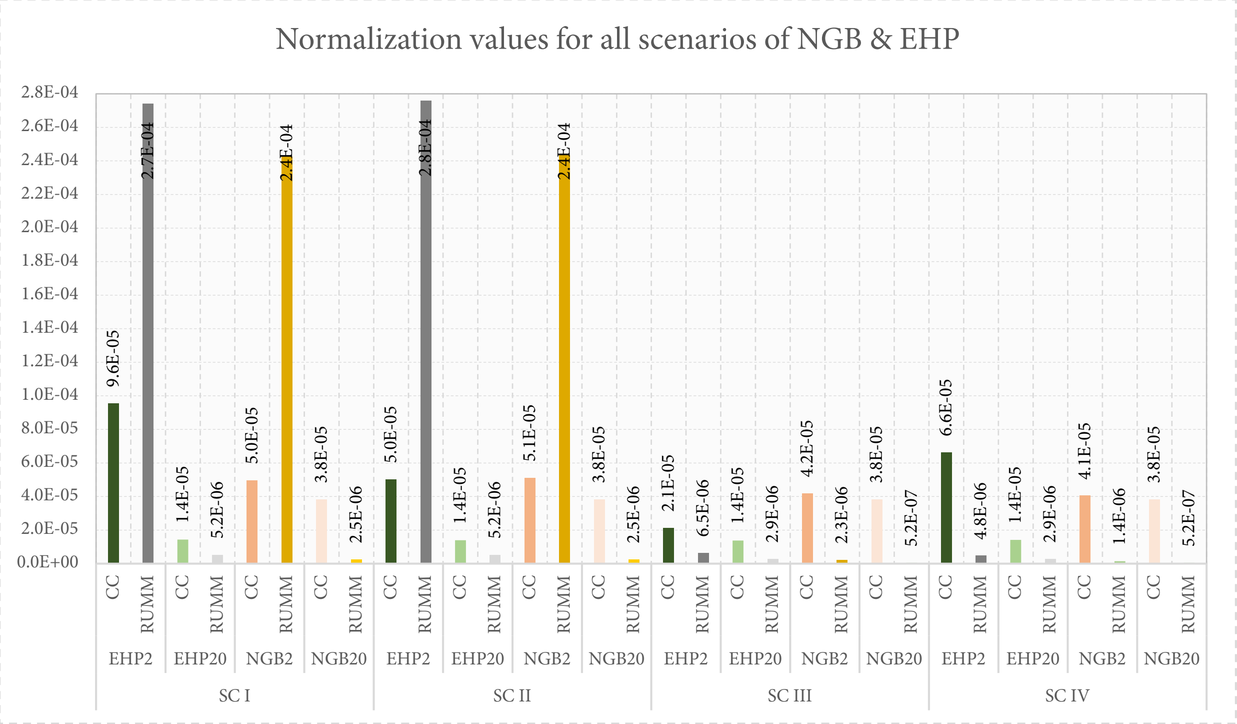


Figure 46- Normalized characterization results considering all scenarios and all case studies.

6.3 Rating system

This section is dedicated to the definition of a rating system for EHP and NGB based on their LCIA results. The rating system is generally adapted from three influencing factors which are presented in the following figure.

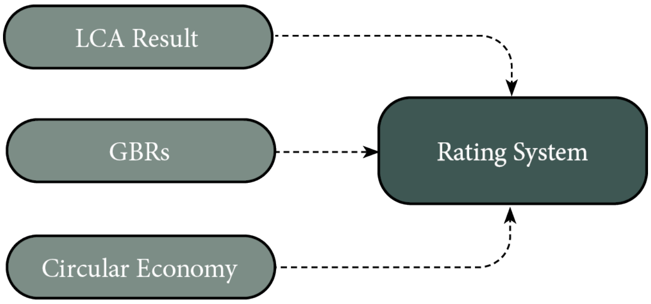


Figure 47- Climate change comparison, NGB and EHP, all scenarios.

6.3.1 Studied impact categories of electric heat pump

This section is dedicated to the definition of a rating system for EHP and NGB based on their LCA results. At the first step, considering the results of LCA of EHP with the life span of two months in scenario I, the most significant factors in two impact categories ("climate change" and "resource use, mineral and metal") are determined. In the diagram below their main influencing factors and their ratio are defined. According to the next figure the "end of life phase" has the most impact on the "climate change [CO_2eq]" with a ratio of 52%, and "component", "manufacturing phase" and "use phase" each makes up consequently 17%, 17% and 14% of it. This is while, in "resource use, mineral and metals", the "component stage" with a ratio of 99% is the dominant factor.

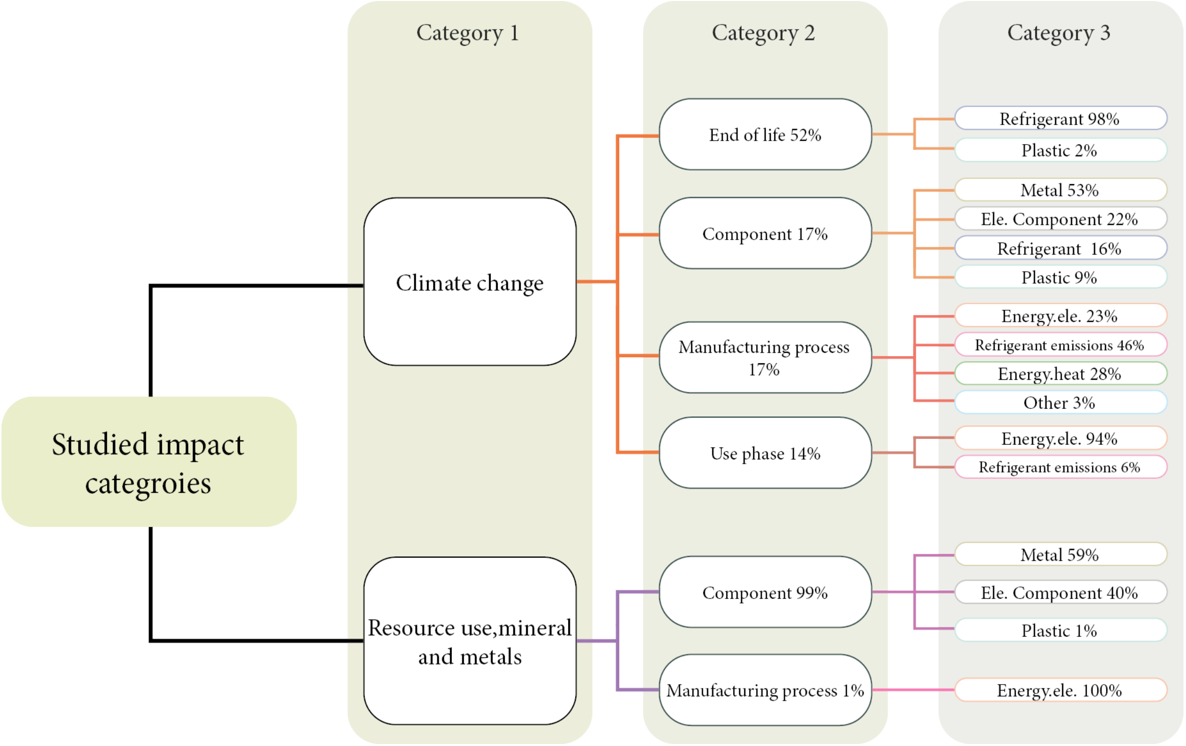


Figure 48- Contribution of main factors (EHP).

By a thorough investigation, it is evident that the refrigerant constitutes 62% of the "climate change" in category 1. This is calculated by multiplication of the ratio of refrigerants indicated in category 3 to the ratio of their relevant stages in category 2 and summing up their results.

A normalized value would be necessary to establish a rating system based on the points assigned to each criterion. The normalization of the results serves as a means of simplifying the interpretation of the results [71]. Due to the different units used in all the impact categories, it is difficult to get an intuitive sense of how they compare. The item to which the data was normalized was determined by the method used. The EN 15804 + A2 method which has aligned their methodology with the EF 3.0 method, except for their approach on biogenic carbon. EF method uses the average impact of a European citizen in the year 2010 as set forth by annex 2 of the Product Environmental Footprint Category Rules Guidance [72]. In normalization, the climate change and resource use, mineral and material are considered.

Normalization values are calculated from characterization values as follows:

$$N = C * f_n$$

Where:

N: Normalized Value [unitless]

C: Characteristic Value [Impact Unit]

f_n: Normalization Factor [Impact Unit -1]

Potential Environmental Impact	Normalization factor
Climate Change	0.0001235
Resource Use, Minerals and Metals	15.71

Table 20- Normalization factor based on EF standard.

As a result of combining climate change, resources, minerals, and metals, the final assigned points are derived. For each substance in each impact category, the normalized values are multiplied by an impact factor of 0.5 (each impact category is considered to have the same influence) and then summed up to obtain a value that illustrates the amount of influenced quantity and the amount of contribution of each substance studied.

As an example, the points of Refrigerant-use management under the category of primary material, is obtained:

The normalized value of refrigerant under the impact category of CC and RUMM in the production phase are equal to **1.05E-05**and **1.35E-06**respectively. This is while the total quantity of the CC and RUMM are **9.56E-05** and **2.74E-04** sequentially. Therefore, the amount of refrigerant constitutes 1.10E-01 of total CC and 4.93E-03 of total RUMM which are multiplied by 0.5 (impact factor) and combine.

Refrigerant (production phase under CC) = [(1.05E-05/ 9.56E-05)] *0.5= 5.50E-02
Refrigerant (production phase under RUMM) = [(1.35E-06/ 2.74E-04)] *0.5= 2.46E-03
Refrigerant (production phase) = (5.50E-02+2.46E-03) = **5.75E-02**

The total value of **5.75E-02** is dedicated to the refrigerant in production phase which are equal to 6%. (Illustrated as the total point). In addition, 1.57E-02 belongs to the combination of CC and RUMM in the phase of component which is equal to 2%. Therefore, 2 points is considered for the refrigerant charge reduction and 4 points for low emitting refrigerant.

Following the same procedure for the rest of the substances, the final ratio is illustrated in the following diagrams.

The percentage of each influencing variable in the final criteria and sub-criteria can be seen in the diagrams below. It is evident that the critical parts are the refrigerant in the CC and the metal and electrical components in the RUMM.

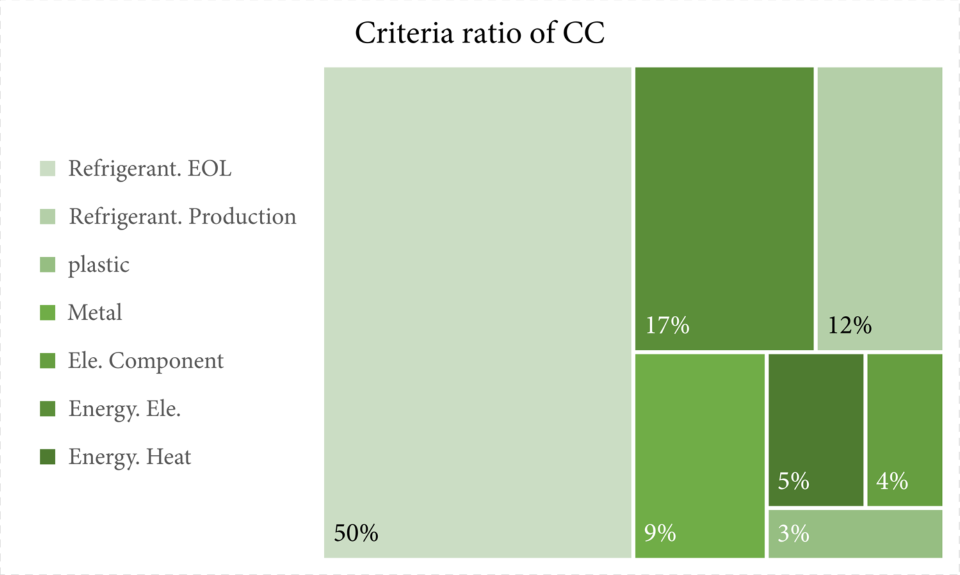


Figure 49- Factor's ratio of "climate change" impact category (EHP, SCI, LS2m).

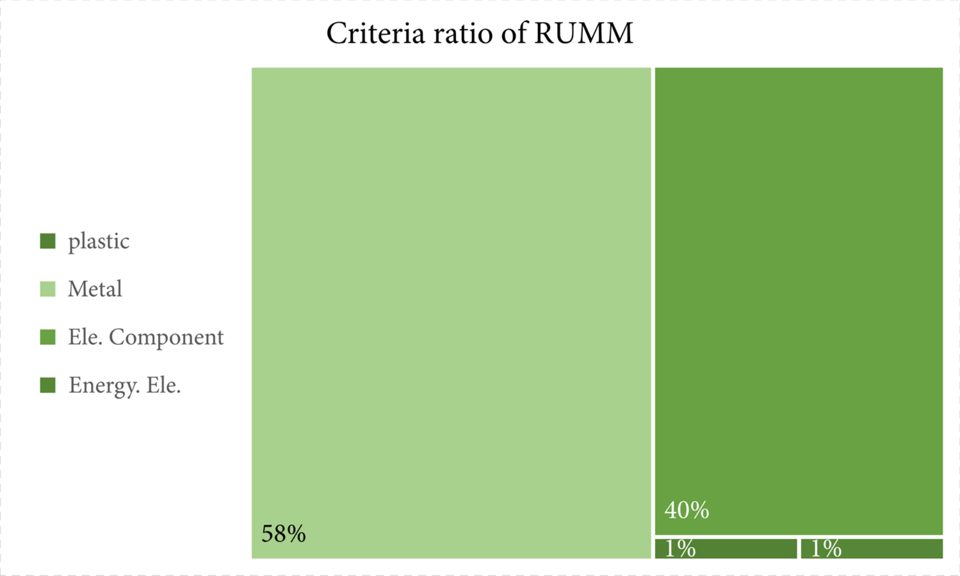


Figure 50- Factor's ratio of "resource use, mineral and metals" impact category (EHP, SCI, LS2m).

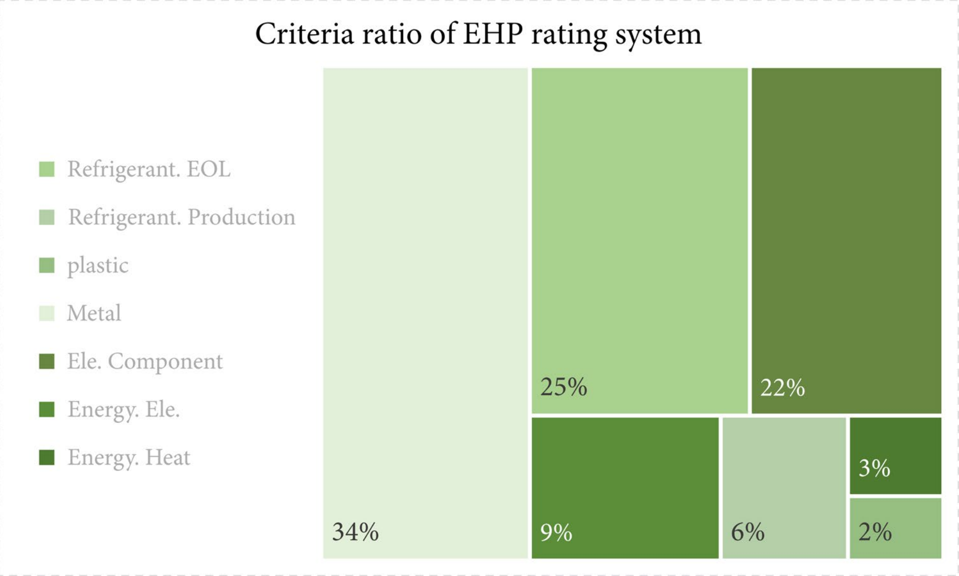


Figure 51- Total points of each sub-criteria after combination (EHP, SCI, LS2m).

The value of CO_2eq emissions profoundly correlates with the alteration of this substance (refrigerant). This is while, metal, with a ratio of 58% of the “resource use, minerals and metals” in category 1, is the most impactful factor. Furthermore, the “energy” factor is one of the main contributors in both impact categories and it would significantly affect the outcomes.

Considering the studies above, the main categories of the rating system are defined, and each factor is assigned to its category accordingly. They are defined as; primary material, energy, and waste to provide the fundamental criteria in the context of this detailed analysis.

According to the succeeding table, refrigerant consumption, metal, and components of the production phase are placed in the first category as the primary material. In comparison, parts of these substances which attribute to the end of life are rearranged in the waste category. Finally, the factors affecting electricity/heat consumption are considered in the energy category.

6.3.2 Criteria of rating system of electric heat pump

In the following, the rating system of the EHP, considering the categories, criteria, sub-criteria, and their assigned points are illustrated.

Category	Criteria	Sub- criteria	Points		Total point	Pre-requisite
Primary Material	Refrigerant-use management	Low emitting refrigerant	4	6	33	-
		Refrigerant charge reduction	2			
	Metal use management	Light weight material/design	10	25		
		Low emitting material	5			
		Scrap/ Recycled/Reused material	10			
	plastic use management	Recycled plastic	2	2		
Energy	Electricity use management	COP optimization	22	31	34	Metering / monitoring
		Modulate the compressor/fan by installing a controller with adaptive control	9			
	Prevention of dissipation of heat	heat recovery system	2	3		
		Natural cooling system	1			
	Top design	Use of renewable energy	Optional			
Waste	Refrigerant emission management	Recovering/ Reclaiming, Recycling refrigerant	15	25	33	-
		Use liquid incinerators	10			
	Waste management (collection for reuse/ reassemble)	Recycled process of leakages	8	8		Leak detection

Table 21- Rating system of EHP.

It should be highlighted that the column of sub-criteria in this table's explanation proposes management techniques for the criterion. These sub-criteria will be thoroughly defined in the following paragraphs.

6.3.2.1 Refrigerant use management

According to the carried-out analysis on the climate change [CO_2eq], it was understood that the most portion of this variation is related to the refrigerant emissions. One part of these emissions released in the production phase of product. Also, the refrigerant leak can cause several issues for a heat pump. Refrigerant selection is based on energy efficiency, safety, reliability, and technical performance, which is why non-flammable HFCs such as R-410A and R-134a continue to be widely used in heat pumps. Direct refrigerant emissions occur during the equipment lifetime (annual losses due to gradual leaks for non-hermetic systems), end-of-life disposal losses and failure losses (rare event). Therefore, to manage this issue some strategies are proposed which can be seen in the following:

6.3.2.1.1 Low emitting refrigerants (refrigerant selection with lowest / zero GWP)

The perfect refrigerant would be non-toxic, non-flammable, non-explosive, non-corrosive, not harmful to the environment, cheap and easy to produce and work with and have good thermodynamic properties operating at low pressures. All refrigerants have an Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) rating. Global Warming Potential (GWP) is the heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of Carbon Dioxide (CO_2). GWP is a measure of how environmentally detrimental refrigerants can be relative to CO_2 which has a GWP of 1.0 [73].

As an example of new generation of refrigerant, R-454b is an HFO (Hydro Olefin) refrigerant made by blending the single component R-32 refrigerant with R-1234yf giving some unique advantages. R-454b also has a lower GWP of 466 compared to R-32 at 675 and has an Ozone Depletion Potential (ODP) of zero. Next generation refrigerants deliver improvements in the Coefficient Of Performance (COP), the ratio of useful heating or cooling provided to work required or energy usage of the compressor [74].

In another case, R-513a is another representative of the new generation of refrigerants which is Non-flammable replacement for R-134a (the refrigerant utilized in the EHP at issue), which has no impact on capacity, near-zero ODP and 55% lower GWP (631 vs. 1430). While the theoretical efficiency drop is about 2%, if used as a drop-in, the actual impact on EHP efficiency has been about 4-6%, depending on application. Another alternative with even greater potential to reduce the GWP would be R1234yf (GWP <1), if available this would lower the GWP of the associated system by over 99%. The choice of replacement might be influenced by the acceptable flammability risk for the specific project, as R513a is non-flammable however R1234yf has low flammability (as defined in ISO:817). R514a (GWP <1) IS another potential alternative in low pressure heat pumps/chillers but cannot be used for high pressure systems [75].

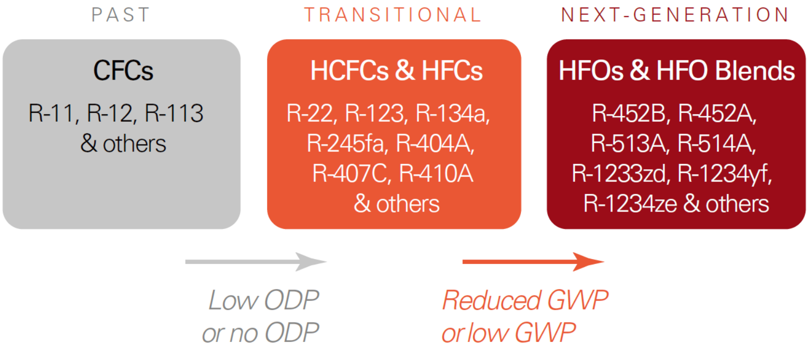


Figure 52- Refrigerant development [73].

6.3.2.1.2 Refrigerant charge reduction

When comparing systems, the GWP of the refrigerant should not be the only consideration, as the refrigerant charge will also have a big impact on the overall effect the system could have, if discharged to atmosphere. For instance, although R410a has GWP 46% higher than R134a, the equivalent 500kW cooling air-cooled chiller has a 62% lower potential impact. Similarly, whilst R513a offers a GWP 70% reduction when compared to R410a, it only delivers a 37% saving in this instance [75].

6.3.2.1.3 Recovery / Reclaim refrigerant

To clarify, reclaimed refrigerant is a refrigerant that has been reprocessed using specialized machinery and tested to meet AHRI Standard 700 purity specifications. Recovered refrigerant is Refrigerant that was removed from refrigeration or air conditioning equipment and stored in an external container without necessarily being tested or processed in any way. Most manufacturers have a methodology that best suits the recovery of refrigerant from their system, to minimize leakage. These methods should always be followed, and ideally undertaken by a contractor trained by that specific manufacturer on the process. In the UK, "Daikin" have launched a scheme called 'Reclaim with confidence'. This scheme is based on Daikin being paid to recover the refrigerant on your site (be it from a Daikin system or not). Daikin will safely remove the refrigerant from site and provide any necessary paperwork.

Other manufacturers may offer similar services. By utilizing a service of this type of the risk of leakage is being minimized during recovery by employing qualified engineers who spend their whole time focused on this process. Daikin has established three routes: simple reclaiming that removes impurities such as oil and water based on the quality condition of the recovered refrigerant, full-scale reclaiming that breaks the refrigerant down by component and then readjusts components at a plant to reclaim the quality as good as that of virgin refrigerant, and destruction for refrigerant that cannot be reclaimed [76].

6.3.2.1.4 Refrigerant Leakage Mitigation

Refrigerant leakage can occur at different steps of the life cycle such as:

- Manufacturing
- Transport from manufacturer to distributor and from distributor to site/pre-charging unit location
- Precharging/Charging/Recharging/Repair/Maintenance/Decommissioning the HVAC system
- Transport of reclaimed refrigerant to suppliers

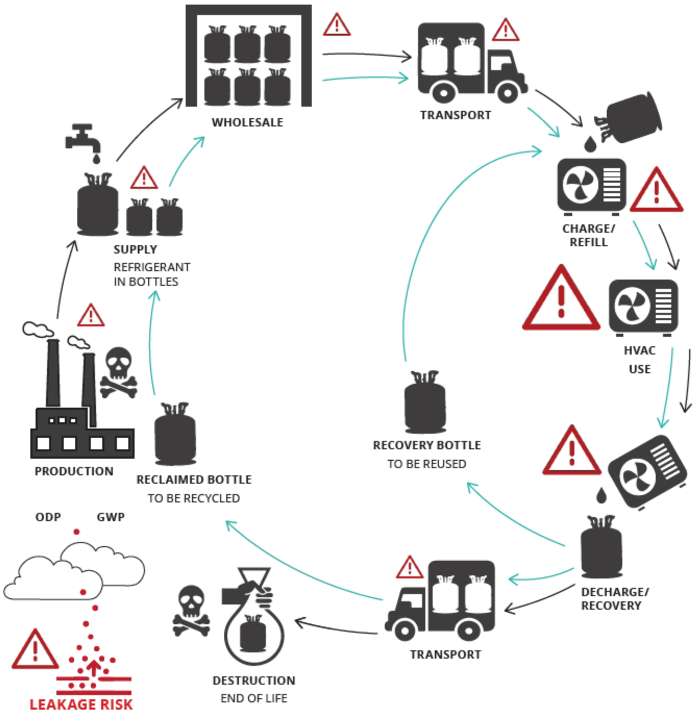


Figure 53- Refrigerant life cycle and environmental impact [77].

Refrigerant leakage mitigation is a key step towards improving the environmental impacts associated with refrigerant use. In Drawdown, Paul Hawken calculates that over 30 years, capturing 87% of refrigerants from equipment leaks and at the end of equipment life would avoid emissions equivalent to 89.7 gigatons (89.7 billion tons) of CO_2eq [77], mitigating actions are based around the priority of dropping the GWP of the refrigerant, then dropping the volume and finally working with factory sealed equipment wherever feasible [78].

6.3.2.2 Metal use management

It is unquestionable that the primary component of the HVAC system's body is composed of metals (steel, copper, aluminum, etc.). The nature of these materials and their properties have a big influence on whether the environmental impact is reduced or increased. The following recommendations are aimed at reducing CO_2eq emissions during production process and when using mineral and metal resources:

6.3.2.2.1 Lightweight materials

the manufacturing of all materials comprising the system also indirectly contribute GHG emissions. Steel, copper, aluminum, and plastics quantities are not widely available and are variable for different brands (e.g., some manufacturers may use more steel in their enclosures where others use more plastics, some use all-aluminum heat exchangers where other use copper-tube aluminum-fin heat exchangers). Improving advanced lightweight materials will have a positive environmental impact, which is in direct relation to the other features of products. For steel, development of more impurity tolerant alloys and improvements to metal collection and sorting processes can improve recycling rates, which may thus reduce steel production from primary resources [78].

6.3.2.2.2 Low emitting material

Ironmaking with pure hydrogen has already been proven at a commercial scale. Direct reduction with green hydrogen would eliminate most of the emissions from steel production. For truly zero-emissions steel the energy requirements of both the direct reduction facility and the electric arc furnace would also need to come from renewable sources. Several European steelmakers foresee renewable hydrogen playing a central role in future production [79].

6.3.2.2.3 Scrap/ recycled, reused material

It has always been common practice to reuse HVAC parts, sometimes requiring repair, refurbishment, or remanufacturing. As an example [80], remanufacturing a diesel engine can save 69% of embodied GHG emissions compared to producing a new diesel engine. If a company purchases a recycled material that has lower upstream emissions than the equivalent virgin material, then this would register as lower emissions in total.

6.3.2.3 Plastic use management

Plastic recycling is currently largely under-developed due to a lack of technologies and low collection and recycling rates for some plastics. Furthermore, downgrading in recycling is problematic. Availabilities of end-of-life materials and energy intensities of recycling processes determine recycling benefits. Recycling is both a demand and supply-side measure: resource recovery is a responsibility of the consumer, and the recycling process is operated by industry. Improve collection rates, use less environmentally impactful recycling technologies, optimization of transport, life-cycle assessment could be some recommendation to manage this strategy.

6.3.2.4 Electricity use management

Heat pumps are important for the electrification of the buildings. Many studies rely on engineering energy efficiency parameters and assume that higher efficiency leads to energy savings. For heat pumps, it is good practice to measure the electricity consumption of the heat pump and other equipment in the heat pump installation. This helps to:

- Determine heat output of the heat pump to monitor the coefficient of performance, seasonal performance factor, and seasonal coefficient of performance.
- Determine the cost of operating the heat pump system.
- Provide diagnostic information in the event of a system fault; and
- Meet the requirements of incentive schemes [81].

In the following several solutions managing the electricity in EHP are proposed.

6.3.2.4.1 COP optimization

The electric grid is still partially powered by carbon-emitting power sources. The first step to decarbonization begins by following some basic principles of applied system design. Decisions for compression-based heating systems should enable a high enough annualized COP to reduce emissions below site-based fossil fuel heating systems. High efficiency systems further reduce wasted energy demand when the right control strategies are applied.

6.3.2.4.2 Modulation

Air conditioning units with conventional fixed capacity compressors are typically designed for peak load performance and usually have more capacity than is required for normal everyday usage. These units turn on and off frequently to reduce output under light load conditions. This can cause broad temperature swings and poor humidity control, as well as decreases in efficiency and overall reliability. Modulating compressor technologies would precisely manage varying temperature and humidity load requirements in the most efficient manner.

6.3.2.4.3 Renewable energy (top design/ optional)

When used in combination with HVAC system solutions that reduce or shift energy demand, renewable energy sources, such as solar and wind, can serve a significant part of a building’s energy demand. As utilities get greener, advanced chiller controls can integrate with services that allow two-way communication with the grid. Buildings that can reduce, shift, or modulate energy use and establish demand flexibility will expedite the reality of a fossil-fuel-free, renewable-energy grid [82].

The focus of this research is to propose effective strategies on how to improve building energy conservation. While renewable energy is emphasized at the top of the design scale, it is regarded as optional rather than mandatory.

6.3.2.5 Prevention of dissipation of heat

Heat dissipation is the movement of heat away from its source into the surrounding environment and this can happen by three methods, conduction, radiation, and convection. It is good practice to measure heat output and heat use. Most heat pump installations need heat metering to detect any heat losses during the operation.

6.3.2.5.1 Installation of heat recovery system

Heat recovery systems reclaim this excess heat energy that is typically expelled from the building and transfers it to different areas where heat is needed. Most used method for heat recovery is a heat exchanger or heat wheel too directly transfer heat to the incoming air. A heat pump can also be used, which make for a more complex system, but the heat recovered can be used for other purposes than heating the ventilation air. Another advantage with using a heat pump for heat recovery is that it can be used for cooling when the outside temperature is hot [83]. The most energy-efficient option is a system that combines a CO_2 heat pump with a heat wheel that can use both exhaust air and outside air [84].

6.3.2.5.2 Natural cooling system

Passive cooling (natural cooling) works in combination with a brine/water or water/water heat pump. In the brine/water heat pump, the brine medium extracts the heat from the heating circuit via a heat exchanger and transfers it outdoors. With the water/water heat pump, the groundwater takes on the task. The natural ambient temperature is also used for cooling. Apart from the control unit and circulation pump, the heat pump remains switched off. As the compressor is not required for this, no power is required. This makes natural cooling a particular energy efficient and inexpensive way to cool the interior of a building.

6.3.2.6 Refrigerant emission management

This carried out analysis in this study, declared that the most portion of refrigerant emission are released in end-of-life phase. The recommendation to reduce this emission are totally different from the production phase. According to the Environmental Protection Agency's (EPA) Clean Air Act of the 1980's it is unlawful to knowingly vent, or otherwise release or dispose of refrigerant in such a manner that permits it to enter the environment. As such, a common task an HVAC service technician will perform when repairing or maintaining a system is the proper handling of refrigerant. In the following some strategies to reduce the refrigerant emissions are proposed.

6.3.2.6.1 Recycling refrigerant

The recycled refrigerant is refrigerant that has been extracted and cleaned for reuse without being tested for compliance with the stringent AHRI Standard 700 purity specifications required for reclaimed refrigerant. When a refrigerator reached the end of its life, after 10–15 years of operation, it may still contain a CFC refrigerant charge. Whether the refrigerator is dumped in a landfill or scrapped in a shredder, its refrigerant charge will finally be emitted to the atmosphere, thus contributing to the depletion of the ozone layer. Recycling machines clean the recovered refrigerant to a given standard they are usually certified. The recycled refrigerant is pumped into a refillable cylinder. Some recycling machines are also equipped to recharge the recycled refrigerant back into the serviced refrigeration system. The cleaning system usually involves an evaporation process, and the refrigerant is passed through a separation chamber, filters, and dryers. Therefore, reusing recycled refrigerants creates savings, since no virgin refrigerant needs to be purchased and no contaminated refrigerant needs to be disposed of [85].

6.3.2.6.2 Liquid incineration

About 90 percent of greenhouse gas emissions from refrigerants comes from end-of-life leaking. By bringing old AC units and fridges to refrigerant management facilities that use liquid incinerators or other methods to destroy as much of the refrigerant as possible, those emissions can be prevented from entering the atmosphere [86].

6.3.2.7 Waste management

Quite a number of HVAC parts can be recycled. However, all the system materials will have to be separated and sorted before being placed in individual bins for recycling. That calls for the right tools, welding experience, and time. Some of the recyclable components are coils, motors, sheet metal, compressors, cardboard boxes, furnaces, copper tubing, brass fittings, metal ductwork. A few parts can't be recycled, such as: tiny plastic components, fiberboard, flex duct, capacitors.

6.3.2.7.1 Collection for reuse/ reassemble

Design for Disassembly (DfD) means that not eventually fewer virgin materials are used in buildings. With the relatively short lead time, it pays for HVAC manufacturers to focus more on the DfD in the design (the simple disassembly of a product) and on the product itself (for the replaceability of parts). DfD in the design also offers the possibility to replace products that are currently not yet circular for a circular variant at a later stage. You increase the circular potential of an installation or building: it also offers the possibility to build in existing or already used products when a circular variant is available, without losing energy or materials [87].

6.3.3 Studied impact categories of natural gas boiler

Similar to EHP, setting the criteria and sub-criteria and allocating points to each of them applies to NGB.

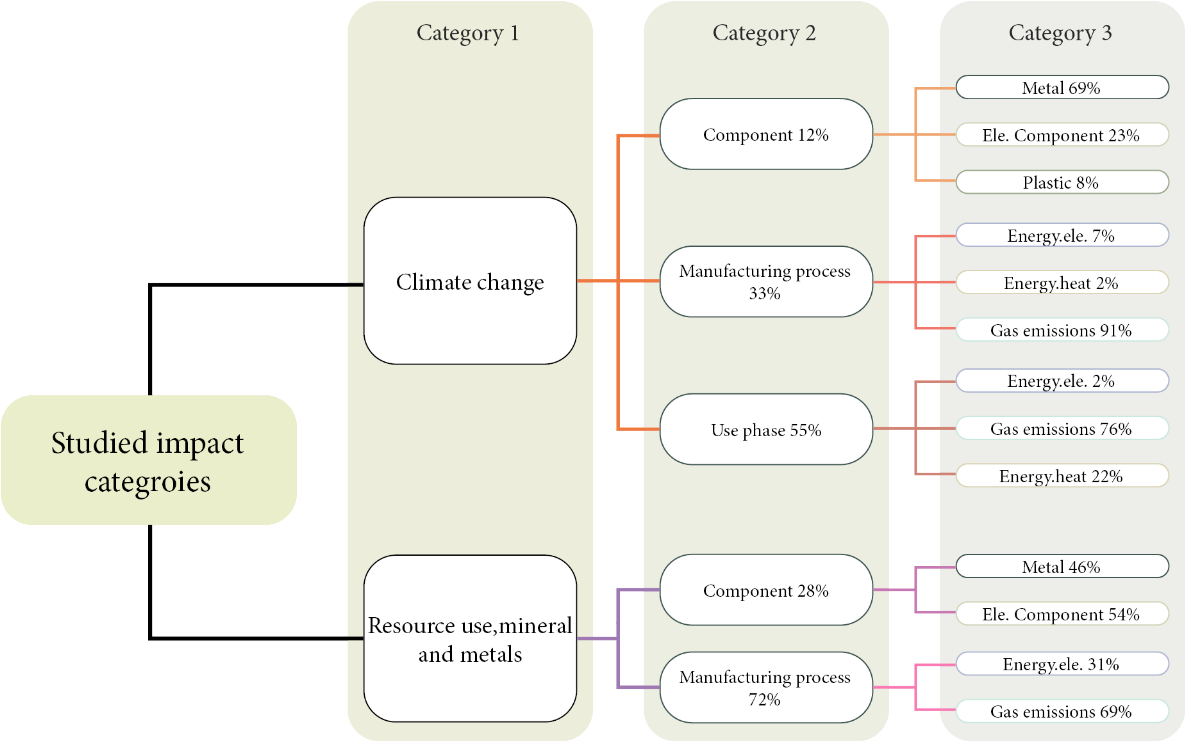


Figure 54- Contribution of main factor (NGB).

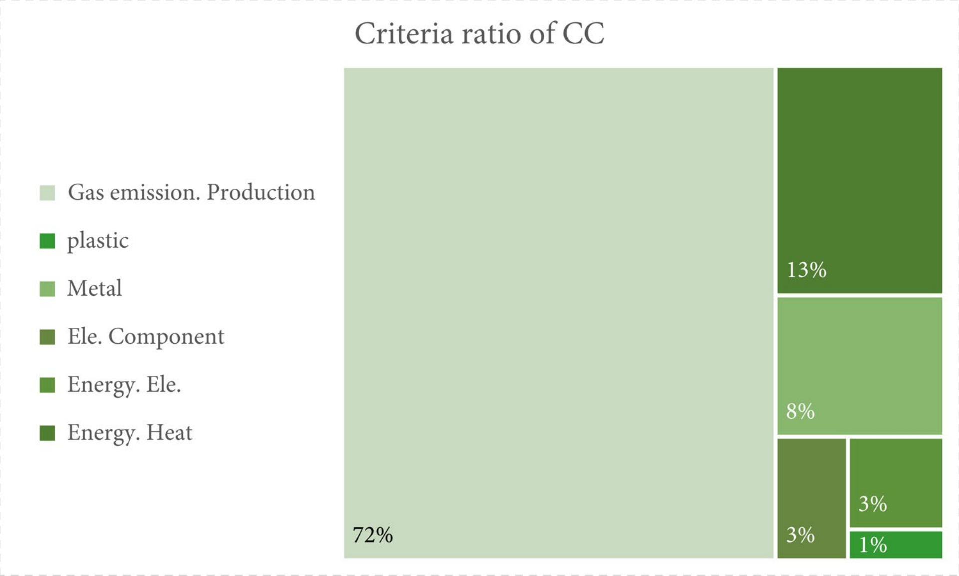


Figure 55- Factor’s ratio of “climate change” impact category (NGB, SCI, LS2m).

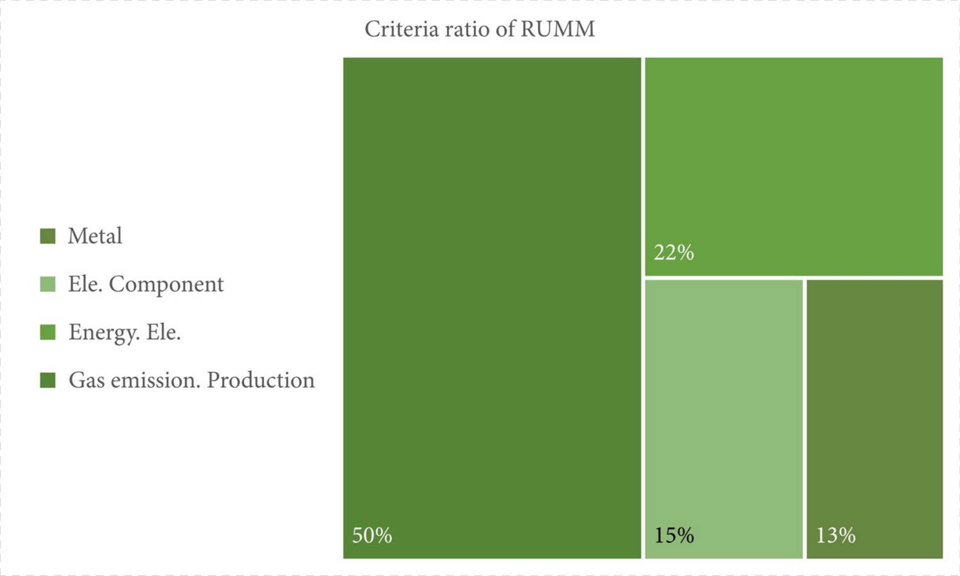


Figure 56- Factor's ratio of "resource use, mineral and metals" impact category (NGB, SCI, LS2m).

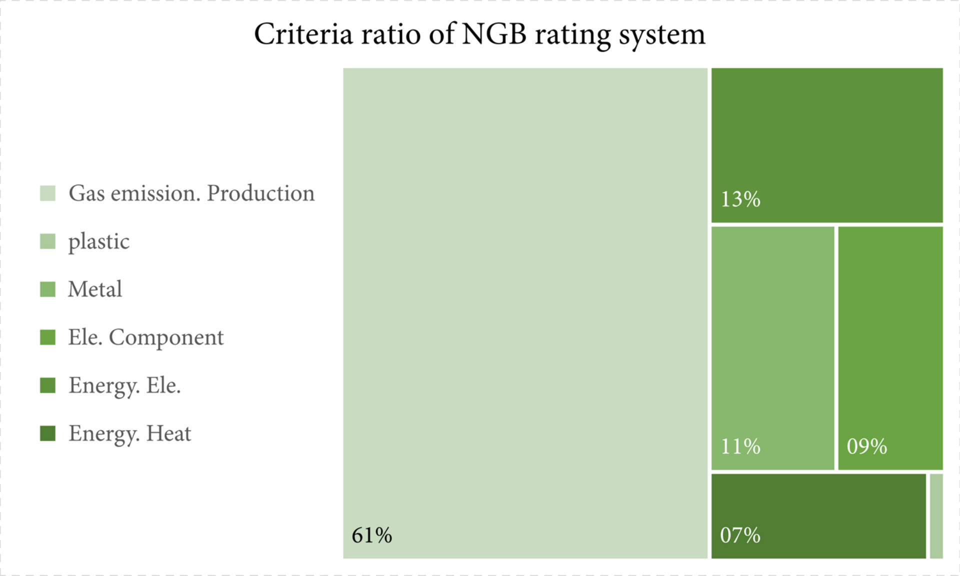


Figure 57- Total points of each sub criteria after combination (NGB, SCI, LS2m).

6.3.4 Criteria of rating system of natural gas boiler

In the following, the rating system of the NGB, considering the categories, criteria, sub-criteria, and their assigned points are illustrated. In the explanation of the next table, related to the NGB, it should be added that the strategies proposed for primary material are relatively similar to EHP. Therefore, in order to prevent the repetition in this part, these topics are neglected. The following is centred around the energy consumption strategies.

Category	Criteria	Sub- criteria	Points		Total point	Pre- requisite
Primary Material	Metal use management	Light weight material/design	3	10	11	-
		Low emitting material	4			
		Scrap/ Recycled/Reused material	3			
	plastic use management	Recycled plastic	1	1		
Energy	Combustion management	COP optimization	13	19	28	Metering / monitoring
	Electricity use management	Adaptive control on electronic components (Modulation)	6			
	Heat management	Reduce slagging and fouling	2	9		
		Reclaiming heat losses	3			
		Insulation	4			
Waste	Gas emissions management	Filtering	12	36	61	-
		Carbon Capture	12			
		Complete combustion	12			
	Waste management (collection for reuse/ reassemble)	Modularity fabrication (Re-use the components)	13	25		Leak detection
		Recycled process of leakages	12			

Table 22- Rating system of NGB.

6.3.4.1 Combustion management

According to the study's findings, the combustion of natural gas and the gases that flow from this process have the most negative impact on the environment. In this section, some strategies to manage this issue would be proposed. The Combustion Control System (CCS) on a boiler, refers to the set of instrumentation and controls that modulates the firing rate of the burner in response to load demand while maintaining the proper air/fuel ratio.

6.3.4.1.1 Combustion efficiency

A boiler's combustion efficiency will increase and heat loss up the stack will be reduced when it is operated with the optimum quantity of excess air. Combustion efficiency is a measure of how effectively the heat content of a fuel is transferred into usable heat. The stack temperature and flue gas oxygen (or carbon dioxide) concentrations are primary indicators of combustion efficiency. Given complete mixing, a precise or stoichiometric amount of air is required to completely react with a given quantity of fuel. In practice, combustion conditions are never ideal, and additional or "excess" air must be supplied to completely burn the fuel. On well-designed natural gas-fired systems, an excess air level of 10% is attainable. An often-stated rule of thumb is that boiler efficiency can be increased by 1% for each 15% reduction in excess air or 40°F reduction in stack gas temperature [88].

6.3.4.1.2 Reduce slagging and fouling of heat transfer surfaces

The lighter fly ash particles produced by coal combustion in boilers are swept away by the hot flue gases, while the denser bottom ash particles settle to the bottom of the boiler. Fly ash particles cause fouling and slagging deposition issues during boiler operation because they adhere to convective heat transfer surfaces and the furnace wall. The boiler's operating efficiency is decreased by the fouling and slagging impact [89].

6.3.4.1.3 Insulation (Radiation losses increase with decreasing load)

Due to the large size of many boilers, the surface area of the outer surface of the boiler is very high, and significant heat loss can occur through the boiler shell. Proper insulation is important to keep these losses to a minimum. The refractory material lining the boiler is the primary insulating material [89].

6.3.4.2 Gas emissions management

This section is devoted to the definition of strategies for reducing the significant quantity of gas emissions produced by combustion.

6.3.4.2.1 Filtering (Separation / purification of CO_2eq emissions)

Gas separation is a significant and widespread industrial process that can be used to produce hydrogen for use as a carbon-free transportation fuel, remove impurities and undesirable compounds from natural gas or biogas, completely separate oxygen and nitrogen from air for industrial and medical uses, and capture carbon dioxide from other gases. Researchers at MIT and Stanford University have developed a new kind of membrane for carrying out these separation processes with roughly 1/10 the energy use and emissions. For example, separating carbon dioxide from methane, these new membranes have five times the selectivity and 100 times the permeability of existing cellulosic membranes for that purpose. Similarly, they are 100 times more permeable and three times as selective for separating hydrogen gas from methane [90].

6.3.4.2.2 Carbon Capture (Demonstrated at the slipstream or pilot-scale)

Carbon Capture and Storage (CCS) involves separation and capture of CO_2 from the flue gas, pressurization of the captured CO_2, transportation of the CO_2 via pipeline, and finally injection and long-term geologic storage of the captured CO_2. Several different technologies can be used to capture CO_2 at the source (the facility emitting CO_2). They fall into three categories:

- Post-combustion carbon capture (Primary method used in existing power plants)

The flue gas from both old and new coal-fired power plants may be treated using Post-Combustion CO_2 Capture (PCC) technology, and it can be deployed to treat all or some of the flue gas. Solvent-based technology, which have been widely used in other applications, now represent the best alternative for PCC from commercial coal-fired power plants [91].

- Pre-combustion carbon capture (largely used in industrial processes)

Pre-combustion capture involves CO_2 removal prior to combustion (applicable to natural gas and to coal-fired Integrated Gasification Combined Cycle (IGCC) power plants). The capture process consists of three stages: the hydrocarbon fuel (typically methane, or gasified coal) is converted into hydrogen and carbon monoxide to form a synthesis gas; CO is converted into CO_2 by water gas shift reaction; CO_2 is separated from hydrogen, which could be combusted cleanly. The CO_2 can be compressed into liquid and transported to a storage site [92].

- Oxy-fuel combustion systems

In an oxy-combustion process, a pure or enriched oxygen stream is used instead of air for combustion. In this process, almost all the nitrogen is removed from the air, yielding a stream that is approximately 95 percent oxygen. Hence, the volume of flue gas, which is approximately 70% CO_2 by volume, from oxy-combustion is approximately 75% less than from air-fired combustion. The lower gas volume also allows easier removal of the pollutants Sulfur Oxide [SO_x], Nitrogen Oxide [NO_x], mercury, particulates) from the flue gas. Another benefit is that because nitrogen is removed from the air, NO_X production is greatly reduced [93].

6.3.4.2.3 Reclaiming boiler system heat losses

Even in an optimized combustion, good percentage of heat varying from 10 to 25% is lost in flue gases. Typically, the temperature of flue gases leaving the stack range from 350°F to 500°F. Thus, there is an ample opportunity to recover some heat from these gases. The waste heat recovery equipment's such as economizer or preheater can be installed to preheat the boiler feedwater or preheat the combustion air. Economizers typically increase the overall boiler efficiency by 3 to 4% [89].

6.4 Conclusion

Environmental life assessment was implemented to investigate two distinct building energy systems to find the critical points influencing the environmental impact in two categories: climate change [kg CO_2eq] and resource use, mineral and metals [kg Sb eq.]. These HVAC technologies, which were evaluated for a temporary period of operation (two months) in mega events in Milan, Italy, were an Electric Heat Pump (EHP) and a Natural Gas Boiler (NGB).

Four alternative business models were taken into account in order to have a more detailed examination of which different stages of the life cycle were evaluated by each of them. The first and second scenarios were proposed with the ownership business model in perspective, whereas the third and fourth scenarios were provided with the rental business model. The life cycle stages included in the LCA of first scenario were production stage (A1-A3), transportation to building site (A4), use phase (B1, B2, B6) and end of life (C1-C4). In the second scenario, the end-of-life phase was not included, but an additional transportation phase (from the user to the organization) was added to the process following the use phase. The use phase (B1, B2, B6) was supposed to be the system boundary for scenario III, however based on the rental business model, it is necessary to include additional phases as well, such as transport from the rental agency to the user, transport from the user to the rental agency, and maintenance. Since, the last scenario was taken into account for final user in the rental circle, the stage of additional transportation from user to the rental agency (stated in scenario III) was excluded, while the phase of end of life was considered. To conduct the LCA, the method "EN 15804 + A2 Method V1.03 / EF 3.0 normalization and weighting set" was used to convert inventory into impact category results and normalize data carried out by SimaPro 9.4.0.1 Educational.

As anticipated, the HVAC systems analyzed in scenario III and IV had less environmental impacts throughout the considered categories, whereas scenario I was selected for further investigation to identify the crucial factors determining the environmental effect. This is due to the fact that this scenario included all phase of the life cycle and represented the worst possible outcome based on the LCA results.

According to the results of this evaluation, it was recognized that the refrigerant input/ output in EHP, natural gas emissions in NGB and primary material and energy consumption in both, play a significant role in variation of results. As a result, since they propose constructive recommendations for reducing environmental impact, they need to be the focus of a more detailed investigation.

After detailed study, all of the recommended strategies categorize in three sections: primary material, energy and waste which were considered same for both case studies. Due to the difference in characteristics of NGB and EHP the criteria were separated.

Regarding EHP, it became evident that managing refrigerants by using the new generation of zero-GWP refrigerants, implementing leakage mitigation techniques during the production and use phases, and reclaiming and recycling substances during the end-of-life phases can significantly reduce environmental impacts.

It was also discovered that the environmental effect of the boiler may be minimized by managing the emitted gas from the combustion process. The explanations for the suggested solutions to this problem were provided by carbon capture, filtration, and boiler heat recovery.

Based on these strategies and contribution of each substance in the LCA results obtained from the analysis on the scenario I for two month- case studies, the EHP and NGB on the question have been rated.

However, because of time restrictions, this research did not involve confirmatory testing to verify this finding. Despite these restrictions, it is anticipated that all proposed approaches would be evaluated in the upcoming research. Moreover, Future development could include more studies such as LCA and statistical analysis of other energy systems and to confirm or deny the validity of these results.

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Appendix I. Electric heat pump

- Analysis of EHP with twenty years life span (Scenarios I, II, III, IV)

Characteristic	Amount	Unit	Source
General information			
Thermal energy produced in life span	267300	kW	-
Nominal heat input	10	kW	Manufacturer data
Refrigerant gases charge	2.753	kg	Conto Termico
Lifespan	20	years	-
Surface	150	m^2	-
Energy needs	89.1	kWh / m^2 /y	-
Mass	72.067	Kg	-
Components (A1-A3)			
Reinforced Steel	40.79	kg	Primary data. Keman et al. 2019
Steel low-alloyed	10.87	kg	Primary data. Keman et al. 2019
Copper	12.11	kg	Primary data. Keman et al. 2019
Elastomer	5.43	kg	Primary data. Keman et al. 2019
Polyvinylchloride	0.54	kg	Primary data. Keman et al. 2019
Refrigerant gas (R134a)	2.75	kg	Famiglietti et al. 2022
Air fan	1.90	kg	ecoinvent
Electronic components	1.00	kg	Kemna et al. 2019 and Ecoinvent
Manufacturing process (A1-A3)			
Water consumption	389.16	kg	ecoinvent
Emissions of water in air	0.06	m^3	ecoinvent
Emissions of water in water	0.33	m^3	ecoinvent
Lubricating oil	2.7	kg	ecoinvent
Electricity	140.00	kWh	ecoinvent
Heat	1365.00	MJ	ecoinvent
Refrigerant gas (R134a) production	0.08	kg	ecoinvent
Refrigerant gas (R134a) leakages	0.08	kg	ecoinvent
Transport input (lorry >32 metric ton, euro5)	21.62	tkm	Keman et al. 2019
Transport input (train)	50.45	tkm	Keman et al. 2019
Packaging			
Plastic film	0.32	kg	Keman et al. 2019
Polystyrene	0.16	kg	Keman et al. 2019
Corrugated board	0.32	kg	Keman et al. 2019
Distribution			
Transport from manufacturer to consumer (freight, lorry 16-32 metric ton, euro5)	36.44	tkm	Keman et al. 2019
Transport from manufacturer to consumer (freight, lorry 16-32 metric ton, euro5)	14.57	tkm	Keman et al. 2019
Transport from manufacturer to consumer (light commercial vehicle)	3.64	tkm	Keman et al. 2019
Use phase (B6)			

Electricity	62162.79	kWh	-
Refrigerant gas production	1.10	kg	PEP ecopassport program
Refrigerant gas leakages	1.10	kg	PEP ecopassport program
Maintenance (B2)			
Components substitution		-	Keman et al. 2019
Transport to consumer	0.36	tkm	Keman et al. 2019
End of life (C2 – C4)			
Copper	97% recycling.11.74	kg	Keman et al. 2019
	3% landfill. 0.36	kg	Keman et al. 2019
Steel	97% recycling .50.11	kg	Keman et al. 2019
	3% landfill .1.55	kg	Keman et al. 2019
Plastic	70% recycling .4.18	kg	Keman et al. 2019
	30% landfill .1.79	kg	Keman et al. 2019
Electronic components	67% recycling 1.94	kg	Keman et al. 2019
	33% landfill 0.95	kg	Keman et al. 2019
Packaging cardboard	83% recycling .0.26	kg	Keman et al. 2019
	6% incineration .0.01	kg	Keman et al. 2019
	11% landfill .0.03	kg	Keman et al. 2019
Packaging plastics	32% recycling.0.15	kg	Keman et al. 2019
	23% incineration.0.11	kg	Keman et al. 2019
	44% landfill.0.21	kg	Keman et al. 2019
Refrigerant gas (R134a)	20% vent into air .0.55	kg	Keman et al. 2019
	80% recycling. 2.20	kg	Keman et al. 2019
Transport from consumer to treatment plant	3.64	tkm	Famiglietti et al. 2021

Table 23- Activity data and references for the EHP (LS.20Y).

- *Scenario I:*

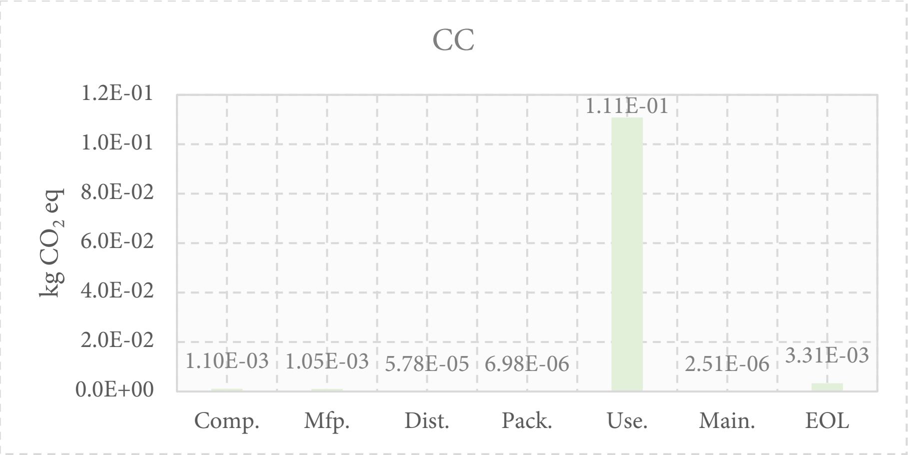

Figure 58- Characterization results of SC. I (EHP I LS 20.Y).

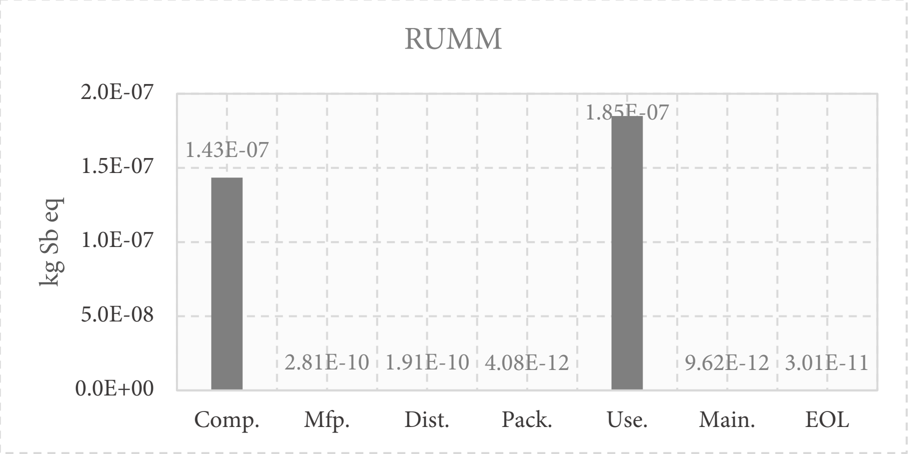

Figure 59- Characterization results of SC. I (EHP I LS 20.Y).

- *Scenario II:*

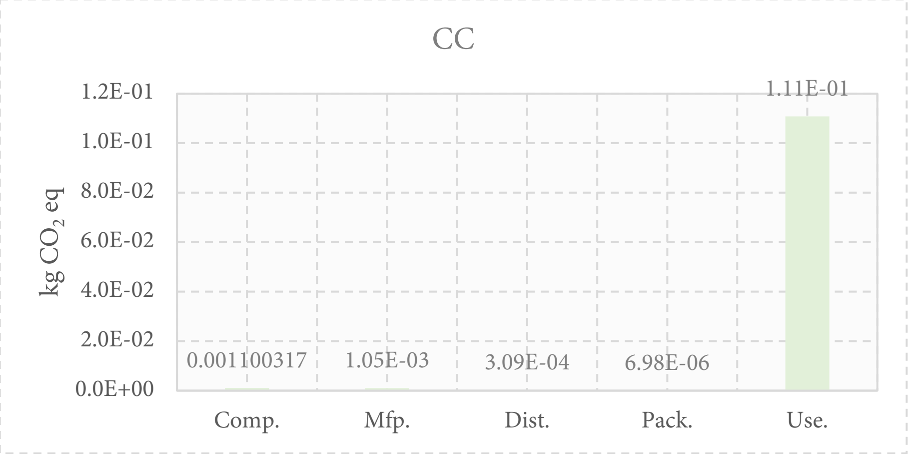

Figure 60- Characterization results of SC. II (EHP I LS 20.Y).

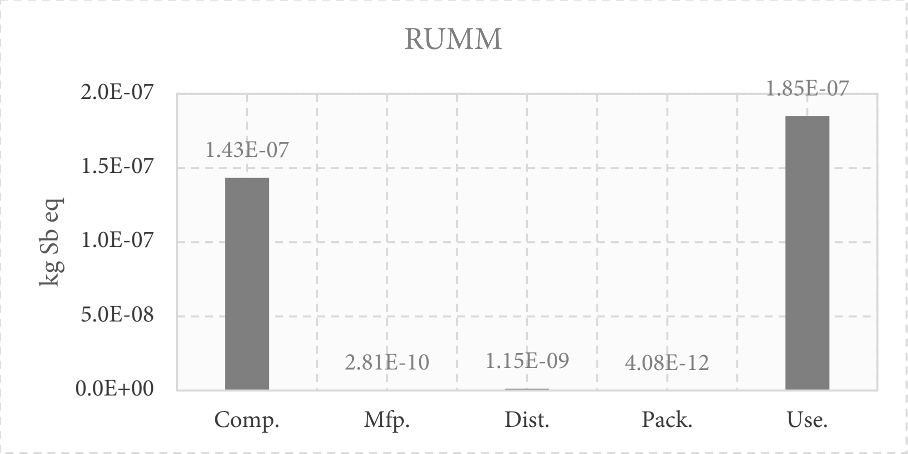

Figure 61- Characterization results of SC. II (EHP I LS 20.Y).

- *Scenario III:*

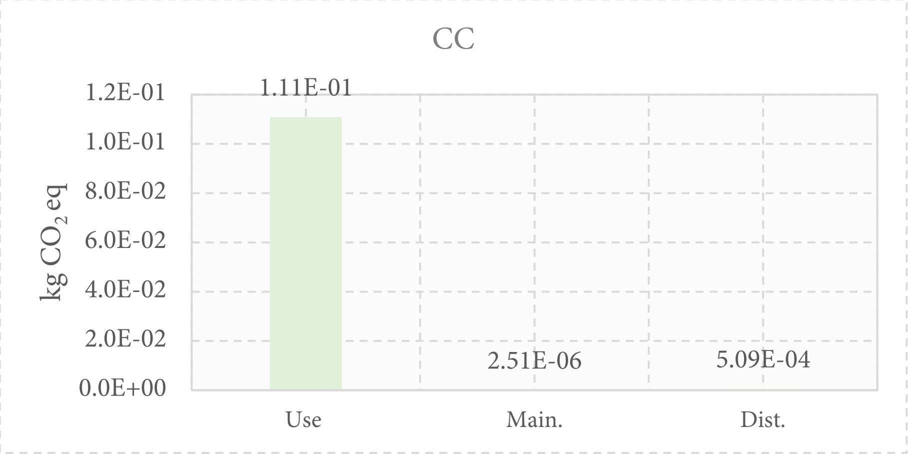

Figure 62- Characterization results of SC. III (EHP I LS 20.Y).

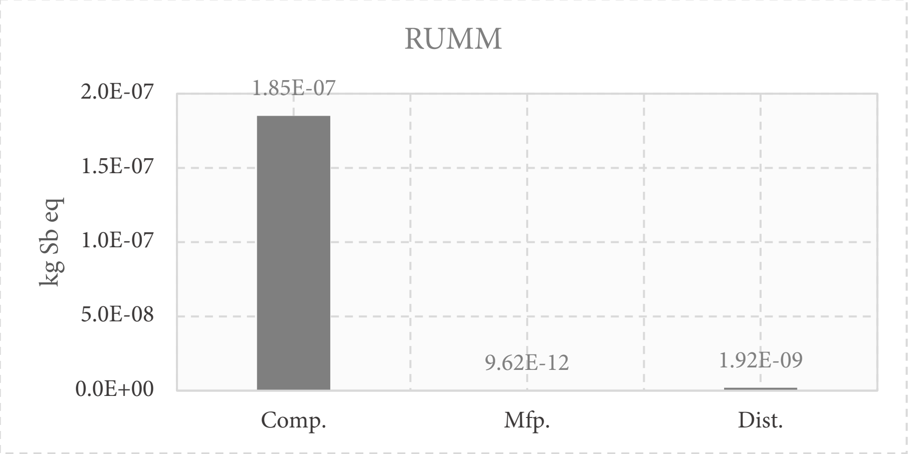

Figure 63- Characterization results of SC. III (EHP I LS 20.Y).

- *Scenario IV:*

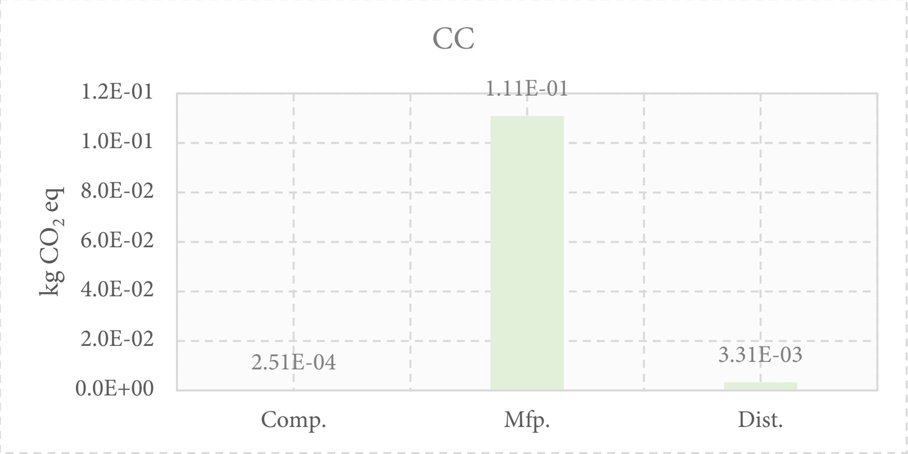

Figure 64- Characterization results of SC. IV (EHP I LS 20.Y).

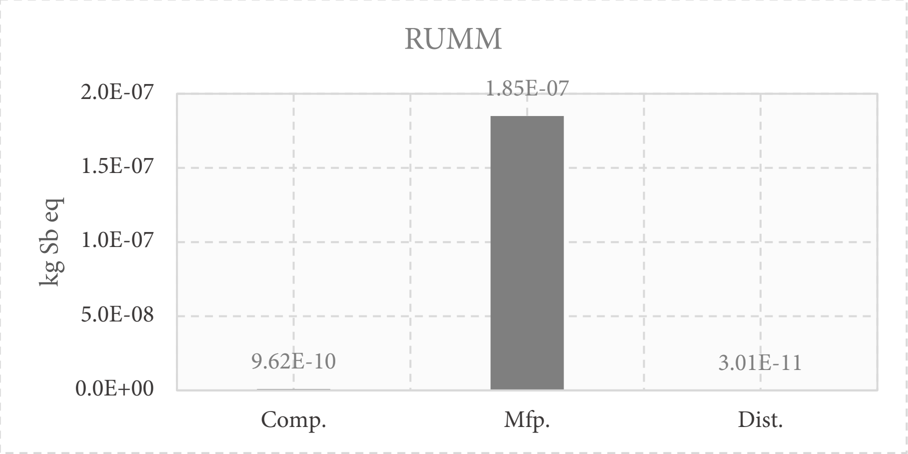

Figure 65- Characterization results of SC. IV (EHP I LS 20.Y).

- *Comparison:*

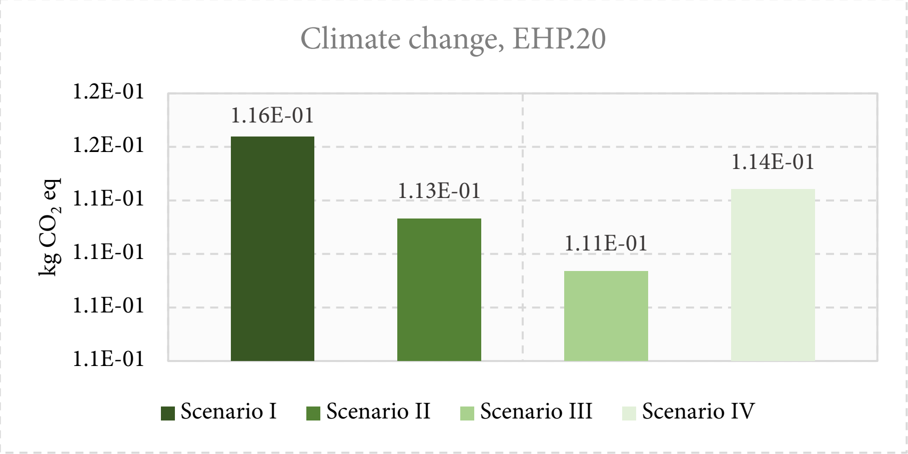

Figure 66- Comparison of characterization results for all scenarios (EHP I LS 20.Y).

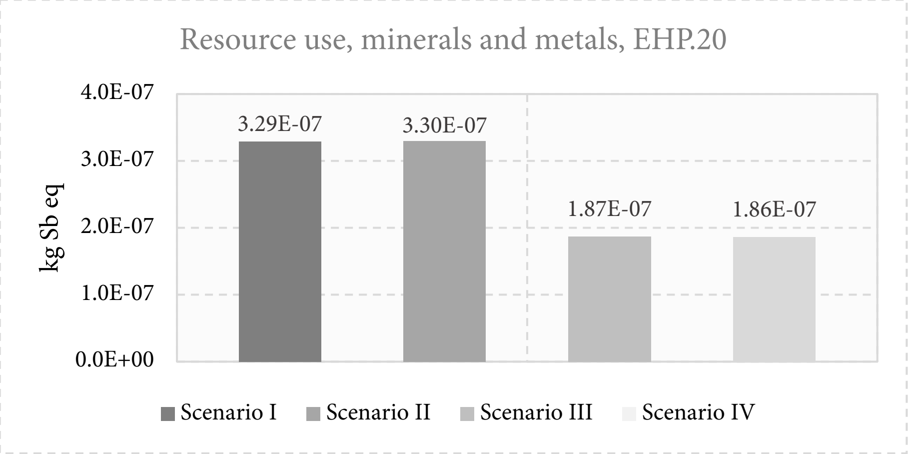

Figure 67- Comparison of characterization results for all scenarios (EHP I LS 20.Y).

Appendix II. Natural gas boiler

- Analysis of NGB with twenty years life span (Scenarios I, II, III, IV)

Characteristic	Amount	Unit	Source
General information			
Thermal energy produced in life span	267300	kWh	-
Nominal heat input	10	kW	-
Efficiency (HHV)	83%	-	Manufacturer data
Lifespan	20	years	-
Surface	150	m^2	-
Energy needs	89.1	kWh / m^2 /y	Assumption
HHV	11.2	kWh / Nm^3	-
Mass	36	Kg	-
Components (A1-A3)			
Reinforced Steel	5.62E+00	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Steel low-alloyed	1.92E+01	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Aluminium	4.61E+00	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Elastomer	1.08E-02	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Polyvinylchloride	1.08E-01	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
ABS	2.34E+00	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Copper	3.53E+00	kg	Primary data, Keman et al. 2019, Famiglietti et al 2021b
Electronic components	1.00E+00	kg	Assumption based on Kemna et al. 2019 ecoinvent
Manufacturing process (A1-A3)			
Welding	4.00E+00	kg	As interpolation of ecoinvent data
Water consumption	1.82E+02	kg	As interpolation of ecoinvent data
Emissions of water in air	0.0272985	m^3	ecoinvent
Emissions of water in water	0.0036398	m^3	ecoinvent
Wastewater treatment	1.51E+02	m^3	ecoinvent
Electricity	2.12E+01	kWh	ecoinvent
Heat	1.85E+02	MJ	ecoinvent
Hazardous waste	2.00E-01	kg	Based on ecoinvent data
Transport input	1.08E+01	tkm	Keman et al. 2019
	2.52E+01	tkm	Keman et al. 2019
Packaging			
Plastic film	1.96E-01	kg	Keman et al. 2019
Polystyrene	9.80E-02	kg	Keman et al. 2019
Corrugated board	1.96E-01	kg	Keman et al. 2019
Distribution			
Transport from manufacturer to consumer	1.82E+01	tkm	Keman et al. 2019
	7.30E+00	tkm	Keman et al. 2019

	1.82E+00	tkm	Keman et al. 2019
Use phase (B6)			
Electricity	3635.28	kWh	Famiglietti et al. 2021b
Natural gas	28754.303	Nm^3	-
Emission to air during the combustion	0.0011594	kg	ecoinvent
Emission to air during the combustion	0.173906	kg	ecoinvent
Emission to air during the combustion	0.4637494	kg	ecoinvent
Emission to air during the combustion	1.159E-05	kg	ecoinvent
Emission to air during the combustion	0.8115614	kg	ecoinvent
Emission to air during the combustion	62675.731	kg	ecoinvent
Emission to air during the combustion	34.781205	kg	ecoinvent
Emission to air during the combustion	0.5796867	kg	ecoinvent
Emission to air during the combustion	0.1159373	kg	ecoinvent
Emission to air during the combustion	3.478E-05	kg	ecoinvent
Emission to air during the combustion	2.318747	kg	ecoinvent
Emission to air during the combustion	23.18747	kg	ecoinvent
Emission to air during the combustion	0.0115937	kg	ecoinvent
Emission to air during the combustion	0.1159373	kg	ecoinvent
Emission to air during the combustion	1.3912482	kg	ecoinvent
Emission to air during the combustion	0.2318747	kg	ecoinvent
Emission to air during the combustion	0.0231875	kg	ecoinvent
Emission to air during the combustion	0.5796867	kg	ecoinvent
Emission to air during the combustion	0.2318747	kg	ecoinvent
Emission to water during the combustion	0.1507186	kg	ecoinvent
Emission to water during the combustion	0.0034781	kg	ecoinvent
Emission to water during the combustion	0.0579687	kg	ecoinvent
Emission to water during the combustion	0.0579687	kg	ecoinvent
Maintenance (B2)			
Components substitution	-		Keman et al. 2019
Transport to consumer	0.18	tkm	Keman et al. 2019
End of life (C2 – C4)			
Copper	3.42E+00	kg	Keman et al. 2019
	1.06E-01	kg	Keman et al. 2019
Steel	2.40E+01	kg	Keman et al. 2019
	7.43E-01	kg	Keman et al. 2019
Aluminium	4.47E+00	kg	Keman et al. 2019
	1.38E-01	kg	Keman et al. 2019
Plastic	1.72E+00	kg	Keman et al. 2019
	7.38E-01	kg	Keman et al. 2019
Electronic components	6.70E-01	kg	Keman et al. 2019
	3.30E-01	kg	Keman et al. 2019
Packaging cardboard	1.63E-01	kg	Keman et al. 2019
	1.13E-02	kg	Keman et al. 2019
	2.15E-02	kg	Keman et al. 2019
Packaging plastics	9.38E-02	kg	Keman et al. 2019
	6.87E-02	kg	Keman et al. 2019
	1.31E-01	kg	Keman et al. 2019
Transport from consumer to treatment plant	1.82E+00	tkm	Famiglietti et al. 2021

Table 24- Activity data and references for the NGB (LS.20y).

- *Scenario I:*

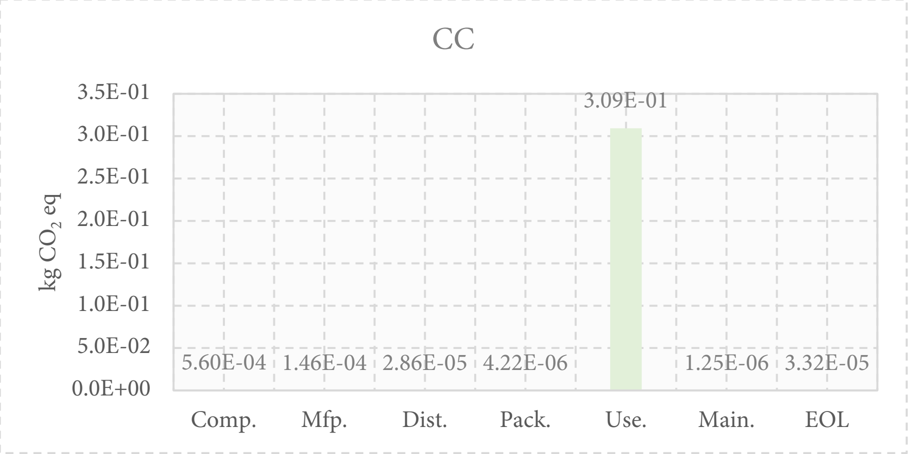

Figure 68- Characterization results of SC. I (NGB I LS 20.Y).

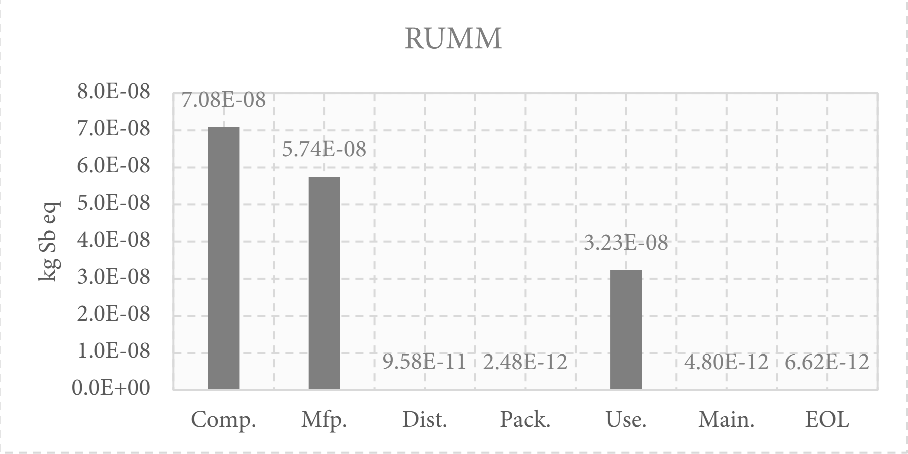

Figure 69- Characterization results of SC. I (NGB I LS 20.Y).

- *Scenario II:*

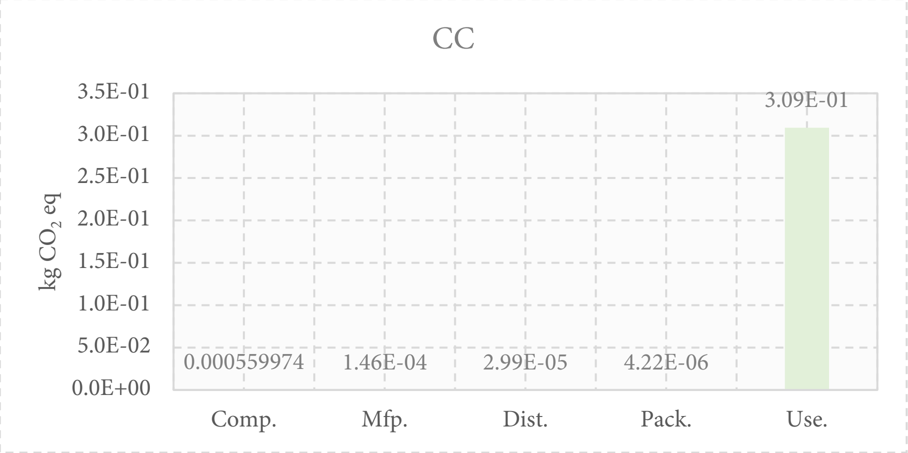

Figure 70- Characterization results of SC. II (NGB I LS 20.Y).

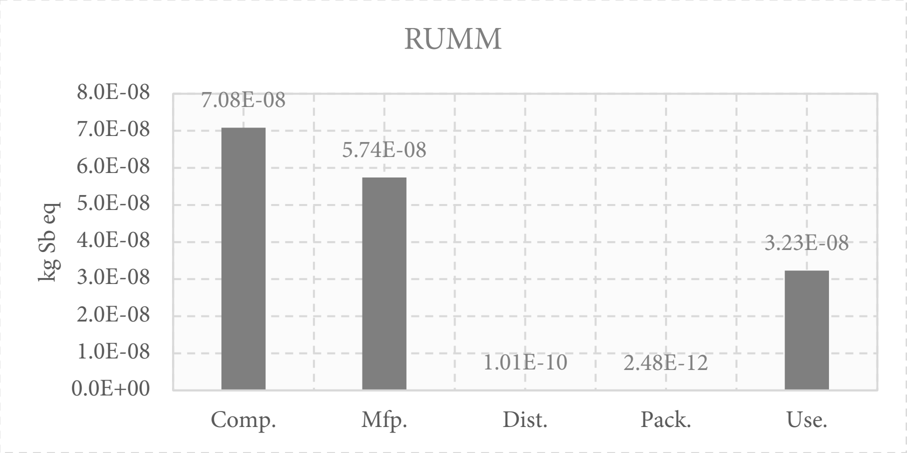

Figure 71- Characterization results of SC. II (NGB I LS 20.Y).

- *Scenario III:*

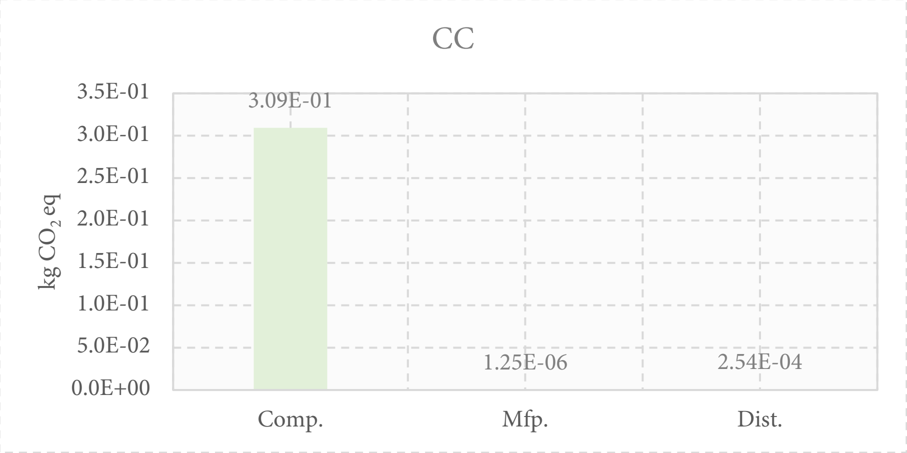

Figure 72- Characterization results of SC. III (NGB I LS 20.Y).

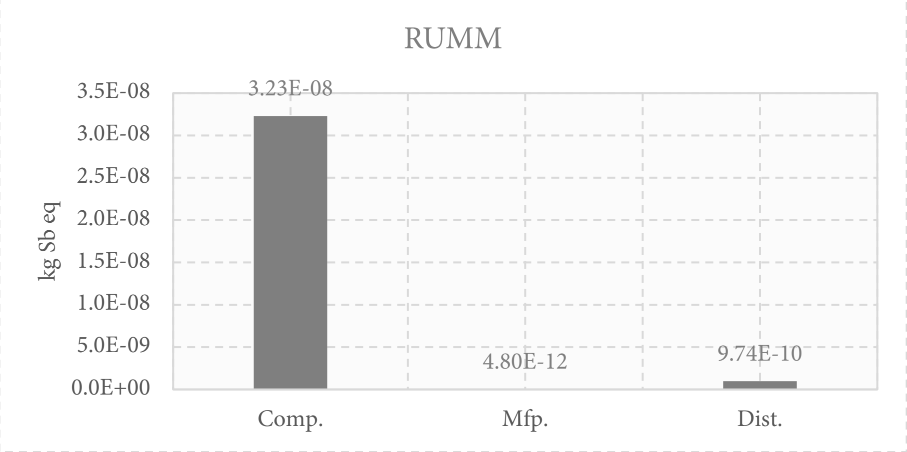

Figure 73- Characterization results of SC. III (NGB I LS 20.Y).

- *Scenario IV:*

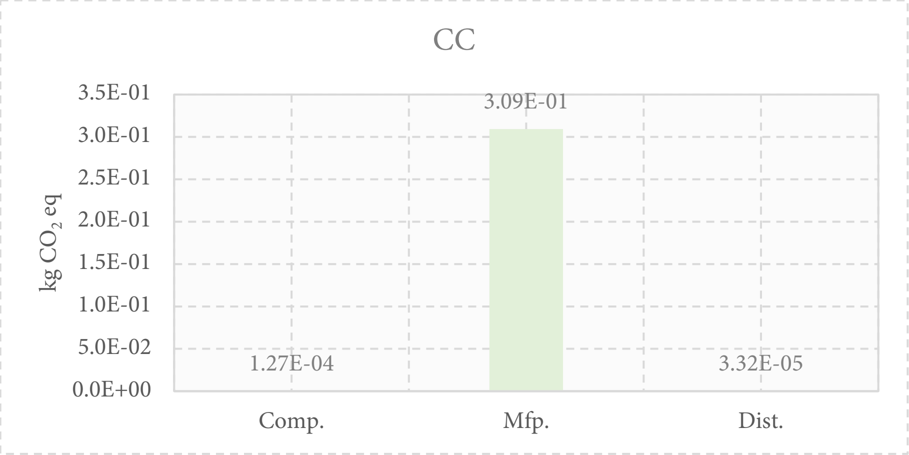

Figure 74- Characterization results of SC. IV (NGB I LS 20.Y).

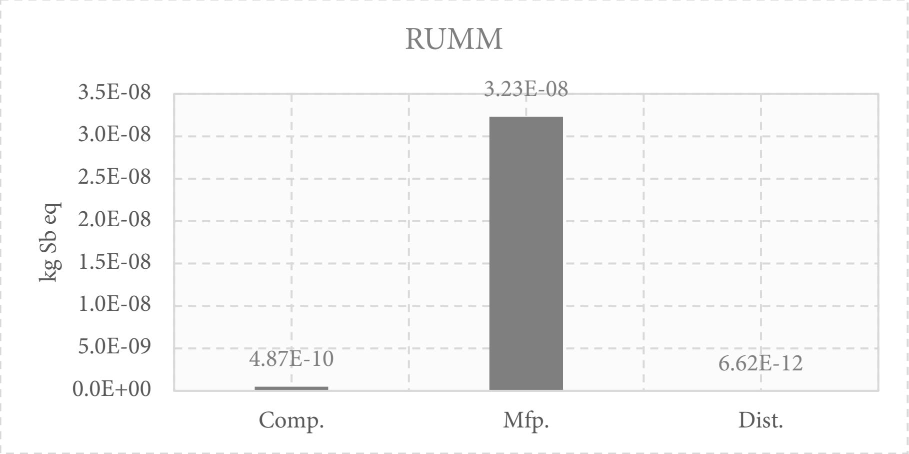

Figure 75- Characterization results of SC. IV (NGB I LS 20.Y).

- *Comparison*:

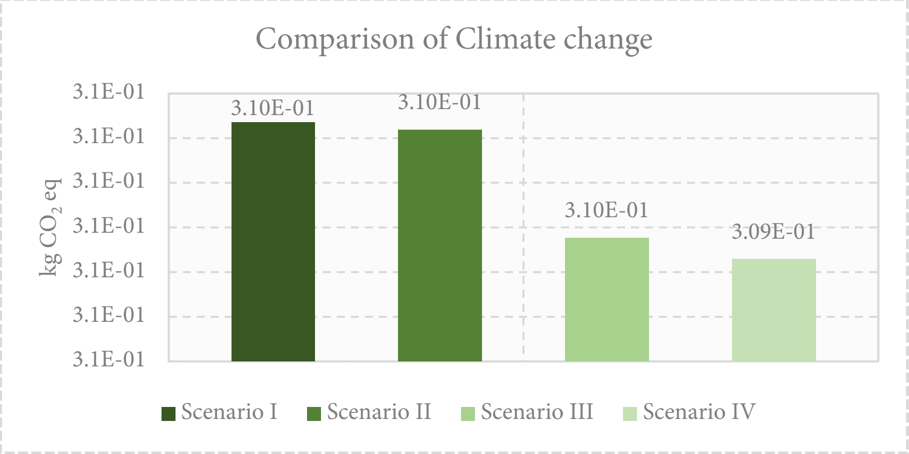

Figure 76- Comparison of characterization results for all scenarios (NGB I LS 20.Y).

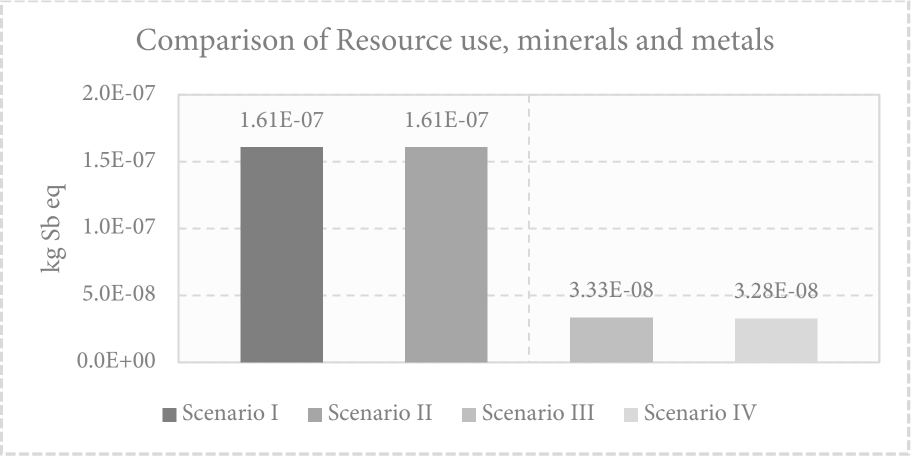

Figure 77- Comparison of characterization results for all scenarios (NGB I LS 20.Y).