POLITECNICO DI MILANO

School of Architecture, Urban Planning and Construction Engineering

MSc in Building and Architectural Engineering

Track Building Engineering

Assessing Environmental Burdens of Heat Emission and Distribution Systems in a Residential Building

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Academic Year 2025-2026

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Abstract

The building sector is currently responsible for approximately **40%** of **global energy-related CO_2 emissions**. While existing literature extensively covers **heat generation technologies**, a significant research gap remains regarding the **environmental impacts** of **emission and distribution networks**. This research investigates the life-cycle environmental performance of three **residential heating system configurations**, Radiators, Radiant Floors, and Fan-coils, within a residential case study in Milan, Italy. Using a 50-year Reference Study Period, the study employs a dual-methodological approach: dynamic energy modeling via IESVE software and a comprehensive Life Cycle Assessment using SimaPro and the Ecoinvent database.

The methodology follows the **ISO 14040/14044 framework**, utilizing a Functional Unit of 1 kWh of delivered thermal energy. The scope encompasses the full life cycle, including the product stage (A1–A3), replacement (B4), operational energy (B6), end-of-life (C3–C4), and benefits beyond the system boundary (Module D). Energy modeling results indicate that the **Radiant Floor system** achieves the **highest seasonal boiler efficiency** (95–96%) and superior **thermal comfort** due to lower operating temperatures (25–30°C), whereas the **Fan-coil system** exhibits the highest auxiliary **electrical consumption**. The **Radiator system**, operating at higher temperatures (50–60°C), shows lower efficiency (88–92%) and **higher natural gas consumption**, along with more intermittent operation and slightly reduced thermal comfort stability compared to the radiant floor system.

The **Life Cycle Impact Assessment** results identify operational energy (**Module B6**) as the dominant environmental hotspot, contributing over 90% to Climate Change and Fossil Resource Use. However, for categories such as Mineral and Metal Resource Use and Freshwater Eutrophication, the product (**A1–A3**) and replacement (**B4**) modules are the primary drivers, collectively accounting for up to **86%** of **impacts** in complex systems like **Fan-coils**. Notably, components such as brass valves can represent 36% of a system's embodied impact despite accounting for only 2% of its total mass. The analysis of **Module D** highlights the critical role of the "avoided burden" approach; recycling high-value metals (steel, copper, and aluminum) offsets over 70% of mineral resource depletion across all systems.

Overall, the **Radiant Floor system** emerged as the **most sustainable configuration** in nearly all categories. This research demonstrates that as buildings become more energy-efficient, the material intensity of technical systems, which can contribute up to 20% of total life-cycle impacts, can no longer be ignored. The findings provide building designers and engineers with essential data to prevent "burden shifting" and support informed decision-making in the pursuit of truly low-carbon residential architecture.

Keywords: Life Cycle Assessment, HVAC systems, Radiant Floor, Embodied Energy, Module D, Residential Sustainability, Milan.

Abstract in Italiano

Il settore edilizio è attualmente responsabile di circa il **40% delle emissioni globali di CO_2 legate all'energia**. Sebbene la letteratura esistente tratti ampiamente le **tecnologie di generazione del calore**, permane una significativa lacuna nella ricerca riguardo agli **impatti ambientali** delle **reti di emissione e distribuzione**. La presente ricerca analizza le prestazioni ambientali nel ciclo di vita di tre **configurazioni di impianti di riscaldamento residenziale**, Radiatori, Pavimenti Radianti e Fan-coil, nell'ambito di un caso studio residenziale a Milano, Italia. Adottando un Periodo di Studio di Riferimento di 50 anni, lo studio applica un approccio metodologico duale: la modellazione energetica dinamica tramite il software IESVE e una **Life Cycle Assessment** (LCA) completa utilizzando SimaPro e il database Ecoinvent.

La metodologia segue il framework **ISO 14040/14044**, adottando come Unità Funzionale 1 kWh di energia termica fornita. L'ambito comprende l'intero ciclo di vita, inclusa la fase di prodotto (A1–A3), la sostituzione (B4), l'energia operativa (B6), il fine vita (C3–C4) e i benefici oltre il confine del sistema (Modulo D). I risultati della modellazione energetica indicano che il sistema a **Pavimento Radiante** raggiunge la **più alta efficienza stagionale della caldaia** (95–96%) e un **comfort termico** superiore grazie alle basse temperature di esercizio (25–30°C), mentre il sistema a **Fan-coil** presenta il maggiore **consumo elettrico ausiliario**. Il sistema a **Radiatori**, operando a temperature più elevate (50–60°C), mostra un'efficienza inferiore (88–92%) e un **maggiore consumo di gas naturale**, unitamente a un funzionamento più intermittente e una stabilità del comfort termico leggermente ridotta rispetto al sistema a pavimento radiante.

I risultati della **Life Cycle Impact Assessment** identificano l'energia operativa (**Modulo B6**) come il principale hotspot ambientale, contribuendo per oltre il 90% alle categorie Cambiamento Climatico e Uso delle Risorse Fossili. Tuttavia, per categorie quali l'Uso di Risorse Minerali e Metalliche e l'Eutrofizzazione delle Acque Dolci, i moduli di prodotto (**A1–A3**) e sostituzione (**B4**) sono i principali responsabili, contribuendo collettivamente fino all'**86% degli impatti** in sistemi complessi come i **Fan-coil**. In particolare, componenti come le valvole in ottone possono rappresentare il 36% dell'impatto incorporato di un sistema pur costituendo solo il 2% della sua massa totale. L'analisi del **Modulo D** evidenzia il ruolo fondamentale dell'approccio "avoided burden"; il riciclo di metalli ad alto valore (acciaio, rame e alluminio) compensa oltre il 70% dell'esaurimento delle risorse minerali in tutti i sistemi.

Nel complesso, il sistema a **Pavimento Radiante** si è affermato come la **configurazione più sostenibile** in quasi tutte le categorie. La ricerca dimostra che, man mano che gli edifici diventano più efficienti dal punto di vista energetico, l'intensità materiale dei sistemi tecnici — che può contribuire fino al 20% degli impatti totali del ciclo di vita — non può più essere ignorata. I risultati forniscono ai progettisti e agli ingegneri edili dati essenziali per prevenire il "burden shifting" e supportare decisioni informate nel perseguimento di un'architettura residenziale realmente a basse emissioni di carbonio.

Parole chiave: Life Cycle Assessment, Sistemi HVAC, Pavimento Radiante, Energia Incorporata, Modulo D, Sostenibilità Residenziale, Milano.

Nomenclature

Roman Symbols

A	Area [m²]
c_p	Specific heat capacity[J/kg·K]
$c_{p,air}$	Air specific heat capacity[kJ/kg·K]
$c_{p,water}$	Water specific heat capacity[J/kg·K]
c_{wrad}	Radiator water content [l]
d	Pipe external diameter [m]
D	Insulation external diameter [m]
l	Pipe length [m]
L	Length [m]
L_{loop}	Length of heating loop [m]
LHV	Lower heating value [MJ/kg]
HHV	Higher heating value [MJ/kg]
$\dot{m}$	Mass flow rate [kg/s]
$\dot{m}_{air}$	Air mass flow rate [kg/s]
$\dot{m}_w$	Water mass flow rate [kg/s]
n	Heat emission coefficient [–]
N_{loop}	Number of loops [–]
N_{rad}	Number of radiators [–]
P	Pressure [Pa]
P_f	Pump effective power [W]
P_t	Pump absorbed power [W]
P_{spec}	Pump specific power [W/(l/s)]
P_{fan}	Fan power [W]
Q	Heat transfer / thermal energy [kWh]
$\dot{Q}$	Heat flow rate [W]
$\dot{Q}_{rad}$	Radiator heat output [W]
Q_{sens}	Sensible heating load [kW]
Q_{need}	Required heat output per floor area [W/m²]
Q_{loss}	Annual heat loss [kWh]
T_{in}	Inlet water temperature [°C]
T_{out}	Outlet water temperature [°C]
T_s	Mean water temperature [°C]
T_{air}	Air temperature [°C]
T_{env}	Environment temperature [°C]
T_{sup}	Supply temperature [°C]
T_{ref}	Reference temperature [°C]
U	Thermal transmittance [W/m²·K]
$\dot{V}$	Volumetric flow rate [m³/s]
$\dot{V}_{air}$	Air volumetric flow rate [m³/h]
$\dot{V}_w$	Water volumetric flow rate [m³/s]

Greek Symbols

Δp	Pressure drop [Pa]
ΔT_w	Water temperature difference [°C]
ΔT_{ref}	Reference temperature difference [°C]
η	Efficiency [–]
η_{fan}	Fan efficiency [–]
λ	Thermal conductivity [W/m·K]
Ψ	Linear thermal transmittance [W/m·K]
ρ	Density [kg/m³]

Subscripts

el	Electrical
env	Envelope
in	Inlet
out	Outlet
rad	Radiator
ref	Reference
sup	Supply
th	Thermal
tot	Total
w	Water

Abbreviations

ACH	Air Changes per Hour
ALCA	Attributional Life Cycle Assessment
CBA	Cost–Benefit Analysis
CLCA	Consequential Life Cycle Assessment
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2-eq	Carbon dioxide equivalent
DHW	Domestic Hot Water
EF	Environmental Footprint
EPBD	Energy Performance of Buildings Directive
ESL	Estimated Service Life
EU	European Union
FCU	Fan Coil Unit
FU	Functional Unit
GLO	Global
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential
HDPE	High-Density Polyethylene
HVAC	Heating, Ventilation, and Air Conditioning
IO	Input–Output
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Megajoule
nZEB	Nearly Zero Energy Building
ZEB	Zero Energy Building
NO_x	Nitrogen Oxides
ODP	Ozone Depletion Potential
PC	Polycarbonate
PE	Polyethylene
PEX	Cross-linked Polyethylene
PVC	Polyvinyl Chloride
RED	Renewable Energy Directive
RSP	Reference Study Period

1. Introduction

This research investigates the environmental effects of different **Heating, Ventilation, and Air Conditioning (HVAC) systems** within a selected residential case study. The central question of this study arises from the need to understand the environmental impacts associated with heating emission and distribution systems, such as radiators, pipes, and related components, used to provide thermal comfort in buildings.

In recent decades, growing global awareness regarding the environmental consequences of human activities has intensified the need to monitor and reduce environmental burdens across various sectors. The building sector, in particular, plays a significant role in resource consumption, energy use, and emissions. Therefore, evaluating environmental impacts throughout the life cycle of buildings related to structure, architecture and HVAC systems has become an important area of research.

This introductory chapter begins by reviewing the existing literature on environmental challenges related to the built environment, with particular emphasis on the role of HVAC systems. It then presents key definitions and technical concepts related to heating systems in buildings. A central focus of the chapter is the methodological framework adopted in this study, namely, the Life Cycle Assessment (LCA) method. The chapter provides an overview of LCA principles, including its definitions, system boundaries, parameters, contexts, and impact categories.

Furthermore, the discussion extends to important influencing factors such as material selection in heating systems and maintenance considerations throughout the operational phase. The content presented in this chapter is compiled from a wide range of literature sources published across different years, aiming to provide a comprehensive understanding of the current research landscape and the position of this topic within the broader scientific discourse.

The chapter concludes by outlining the novelty of the present research and clarifying the objectives and structure of the subsequent chapters. Ultimately, the findings of this study are expected to contribute valuable insights for related research areas and, more specifically, to support informed decision-making during the design phase of buildings, particularly in the selection of technical heating systems.

1.1. Environmental challenges of the built environment and policy responses

The depletion of natural resources, environmental degradation, and increasing pollutant emissions have intensified global concern regarding the environmental performance of the built environment. Buildings and construction-related activities have been consistently identified as major contributors to these challenges due to material extraction, construction and demolition processes, system maintenance, and, most significantly, energy consumption for space conditioning and domestic hot water production [1][2][3].

Across multiple studies, the **building sector** is reported to account for a substantial share of global and regional energy use and greenhouse gas emissions. At the global scale, the built environment is responsible for approximately **40% of annual energy-related CO_2 emissions**. Within this share, **building operations account for around 27% of emissions**, including both direct and indirect contributions, while **building materials and construction processes (commonly referred to as embodied carbon) contribute an additional 13%** annually. In parallel, buildings represent approximately **35% of global final energy consumption**, highlighting their central role in both energy use and carbon emissions.[4] [3][5].

At the European level, the building sector is a major contributor to environmental impacts, being responsible for approximately **35% of total final energy consumption**. Within households, heating systems for space heating and domestic hot water (DHW) account for nearly **80% of total energy use**, highlighting their dominant role in residential energy demand. Consequently, reducing emissions associated with heating is of paramount importance, particularly in light of future climate projections, which indicate a potential decrease in heating demand alongside a significant increase in cooling demand in Southern and Central Europe. This trend is further reinforced by the fact that cooling demand is currently the fastest-growing energy end-use in buildings, indicating a shift in future operational energy profiles [6] [7]

Energy consumption patterns in the residential sector further emphasize the importance of space heating. According to Eurostat (2022), **space heating accounts for approximately 63.4% of household energy consumption in Europe and 67.3% in Italy**, making it the largest energy end-use compared to water heating, appliances, and cooking. This confirms that space heating is the primary driver of residential energy demand. In addition, space heating emissions significantly exceed those of other household energy uses, being several times higher than emissions associated with lighting and appliances, further underlining its dominant environmental impact [8]

A more detailed analysis of the energy sources used for space heating reveals a strong dependence on fossil fuels, particularly natural gas. At the European level, **natural gas accounts for approximately 36.3% of energy used for space heating**, followed by renewables and biofuels (31.4%). In contrast, Italy shows a significantly higher reliance on natural gas, reaching **56.8%**, while the share of renewables is comparatively lower (32.2%). This highlights a greater dependence on fossil fuels in the Italian residential sector compared to the European average, with important implications for both environmental sustainability and energy security [8]

Given this significant contribution of the building sector to energy consumption and emissions, **robust policy and regulatory frameworks have been developed**. Key institutions such as the **International Energy Agency (energy analysis and policy guidance)**, **Eurostat (harmonized energy and emissions data)**, and the **Intergovernmental Panel on Climate Change (climate science and mitigation pathways)** provide the foundation for understanding and addressing these challenges.

At the European level, these challenges are addressed through **a structured framework of directives, regulations, and technical standards**. Core legislative instruments include the **Energy Performance of Buildings Directive (EPBD)**, the **Energy Efficiency Directive (EED)**, and the **Renewable Energy Directive (RED)**, which define binding requirements for improving energy efficiency and increasing renewable energy use. Additionally, **Regulation (EU) 2020/852 (EU Taxonomy)** ensures that sustainability measures do not create negative impacts in other environmental areas. These are supported by technical standards such as **EN ISO 52000, EN 15978, and EN 15804**, which provide **harmonized methodologies for energy performance and life cycle assessment (LCA)**.

To address emissions from the building sector, the EU has established ambitious targets, including **a 55% reduction in greenhouse gas emissions by 2030** and **climate neutrality by 2050**. These are implemented through major initiatives such as the **European Green Deal**, **Fit for 55**, and the **Renovation Wave**. The **revised EPBD (2024)** is particularly important as it **elevates the existing nearly zero-energy building (nZEB) standard, first introduced in 2010, to the more stringent zero-emission building (ZEB) requirement**, while also introducing mandatory life-cycle carbon assessment. In addition, policy focus is shifting from individual buildings to **district-scale solutions such as Positive Energy Districts (PEDs)**, which integrate renewable energy and energy sharing systems [9], [10].

At the national level, these European directives are implemented through local regulations. In Italy, particularly in Lombardy, **Decree DGR n. 3868/2015** enforces **Energy Performance of Buildings Directive (EPBD)** and the **Energy Efficiency Directive (EED)** requirements through **Energy Performance Certificates (EPCs)**. Furthermore, **Life Cycle Assessment (LCA) based on ISO 14040–44** is used to evaluate environmental impacts across the entire building life cycle. Practical implementation strategies include **low-impact materials, advanced heating and cooling systems, and on-site renewable energy technologies**, all contributing to the decarbonization of the building sector [9], [10].

Beyond policy implementation, it is important to consider the role of technical building systems in contributing to environmental impacts across the life cycle. In addition to operational energy use, embodied emissions associated with materials, manufacturing, and installation represent a significant share of total impacts. At the global level, building material production accounts for approximately 5% of total energy use and 10% of carbon dioxide emission. Within buildings, technical systems such as HVAC and ventilation installations can contribute between 5% and 20% of total life cycle impacts, with a higher share observed in embodied environmental impacts [3].

Recent studies further highlight that, while the use phase—primarily driven by heating and cooling—remains the dominant contributor to environmental impacts in conventional buildings, the relative importance of embodied emissions is increasing. This is particularly evident in high-efficiency buildings and long service lifetimes, where embodied impacts can become comparable to operational impacts. This shift emphasizes the importance of adopting a comprehensive life-cycle perspective that integrates both energy performance and material-related impacts in the evaluation of building systems [5].

1.2. Heating-related technical systems in residential buildings

Within residential buildings, heating systems are commonly structured into three interconnected components: heat generation, heat distribution, and heat emission. These components jointly determine the thermal performance, energy demand, and material composition of the overall heating system [2], [11].

1.2.1. Heat generation systems

Heat generation in residential buildings has traditionally been based on individual boilers, with distinctions made according to efficiency level and operating principle. Conventional non-condensing boilers and high-efficiency condensing boilers are widely referenced as common heat generation technologies in apartment-scale applications. In addition to boiler-based systems, heat pumps using air, water or soil as a heat source represent an alternative generation technology, particularly relevant in energy-efficient buildings [2].

1.2.2. Heat distribution systems

Heat distribution systems connect the heat generation unit to the emission devices and are characterized by their operating temperature and material composition. High-temperature heating systems, typically operating at supply and return temperatures around 90/70 °C, commonly employ steel piping. In contrast, low-temperature systems operating at approximately 55/45 °C allow for the use of plastic piping materials, such as cross-linked polyethylene (PE-Xc), due to reduced thermal and pressure requirements [2].

The choice of distribution materials also varies across emission technologies. Radiator-based systems typically use steel or copper piping, while floor heating systems utilize polymer-based materials such as polyethylene or polybutene for embedded pipe networks [11].

1.2.3. Heat emission systems

Heat emission systems transfer thermal energy from the generation unit to the indoor environment. Radiators are identified as the primary emission system in residential heating applications. Their design and required surface area are strongly influenced by the operating temperature level of the system. In low-temperature heating systems, radiators must provide a significantly larger radiating surface compared to those used in high-temperature systems in order to deliver the same thermal output. This relationship directly links emission system design to the selected heat generation technology and supply temperature regime [2].

In addition to radiators, alternative emission systems are used in residential buildings. Floor heating systems rely on embedded piping networks to distribute heat over large surface areas, enabling effective operation at lower supply temperatures. Fan coil convectors represent another emission technology, combining forced air movement with hydronic heat exchange to deliver space heating with higher cost of production and use [11].

The selection of materials for emission systems is contingent upon the system's operating temperature and the prevailing building conditions. Radiator heating systems consist primarily of heating panels manufactured from steel or aluminium, connected through piping systems made of steel or copper. Floor heating systems are composed of polymer-based piping materials integrated within the building structure, enabling low-temperature heat delivery over extended surface areas. Fan coil convectors comprise multiple material components, including a galvanized steel base, a fan section equipped with a cross-flow tangential fan, an electric motor, and a heat exchanger constructed from copper tubes and aluminium fins [11].

1.3. LCA Methodology; Phase Definitions within the Built Environment

Life Cycle Assessment (LCA) is consistently identified as the primary **methodological framework** for evaluating environmental performance in the built environment. LCA is defined as a quantitative method that assesses resource consumption and environmental impacts associated with a product or process over its entire life cycle, from raw material extraction through production, use, and final disposal, commonly referred to as a cradle-to-grave approach [1], [12]. By accounting for impacts across all life cycle stages, LCA enables comprehensive environmental evaluation and supports the avoidance of burden shifting between different environmental categories or system phases [3].

Within the context of building systems, LCA is applied to quantify both operational energy use and material-related impacts over the full service life of a building. This integrated perspective allows for the comparison of impacts generated during production and disposal with those occurring during operation, enabling the identification of environmental impact payback periods, where initial environmental burdens may be offset by operational energy savings over time [1].

Across the literature, LCA is described as a structured methodology composed of **four main phases**. The first phase, **goal and scope definition**, establishes the objectives of the study and defines system boundaries. The second phase, **life cycle inventory** analysis, involves compiling and quantifying all relevant inputs and outputs, including material flows, energy use, and emissions to the environment. The third phase, **life cycle impact assessment**, translates inventory data into potential contributions to environmental impact categories, often using reference substances to enable comparison across different impact types. The final phase, **interpretation,** evaluates results in relation to the defined goals, frequently involving normalization against regional or annual environmental impacts or comparison with findings reported in the literature [2], [11].

The methodological framework of LCA is internationally standardized through the **ISO 14000** series, particularly **ISO 14040** and **ISO 14044**, which define principles, requirements, and guidelines for conducting LCA studies [11], [12], [13]. These standards have provided a consistent basis for LCA application across sectors, including building construction and technical systems. In the European context, LCA methodologies for buildings have been further harmonized through standards such as **EN 15643-2** and **EN 15978**, which specify quantitative assessment categories for evaluating environmental performance at the building level [13].

Several sources emphasize the role of LCA as part of a broader set of tools used to assess environmental sustainability. While methods such as Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), and Cost–Benefit Analysis (CBA) are also applied in environmental decision-making, LCA is distinguished by its system-wide perspective and its ability to capture interactions across multiple life cycle stages [11]. This comprehensive scope has positioned LCA as one of the most actively used techniques for addressing environmental challenges associated with products, processes, and buildings.

In advanced building-related applications, LCA is increasingly applied using integrated approaches that aim to cover the entire building life cycle and all construction products, including technical equipment such as heating, ventilation, and distribution systems. Integrated Life Cycle Assessment (iLCA) approaches seek to ensure that both structural elements and building services are consistently included within the same analytical framework, enhancing comparability and completeness of environmental evaluations [13].

From a conceptual standpoint, LCA operates across multiple interrelated domains. The technosphere represents technological processes and material flows, the ecosphere describes interactions with ecological systems, and the valuesphere reflects human valuation and interpretation of environmental impacts. Considering these spheres jointly supports a structured interpretation of results and strengthens the relevance of LCA outcomes for environmental decision-making [11].

1.3.1. LCA Approach & Modelling

Life Cycle Assessment (LCA) can be classified into different modeling approaches depending on the research objectives and the methods used for inventory analysis. A primary distinction is made between **Attributional LCA (ALCA)** and **Consequential LCA (CLCA)**. Attributional LCA describes the environmental impacts associated with a specific product system under existing conditions, whereas Consequential LCA evaluates the environmental consequences of changes in demand or decision-making processes.

In addition, Life Cycle Inventory (LCI) modeling can be performed using different approaches, including **process-based (bottom-up)**, **input–output (IO) (top-down)**, and **hybrid methods** that combine both. The process-based approach is the most widely applied, as it provides high resolution for product systems and allows detailed representation of industrial processes and physical flows. This approach is particularly suitable for identifying environmental hot-spots within a system and is commonly used for quantifying the environmental profile of specific products and services.

Although hybrid approaches aim to combine the advantages of process-based and input–output methods—particularly to reduce system boundary cut-offs—the process-based approach remains the dominant method in detailed technical assessments, including studies on heating technologies [14].

In addition to modelling approaches, the selection of data sources and impact assessment methods plays a critical role in ensuring the robustness and comparability of LCA results.

At the level of building elements and construction products, **EN 15804 +A2 (2019)** establishes the **core rules for Environmental Product Declarations (EPDs)**, enabling **consistent life cycle assessment of materials and technical components**. In addition, **ISO 14067 (2018)** provides **guidelines for quantifying the carbon footprint of products**, supporting detailed evaluation of greenhouse gas emissions at the component level. These approaches are complemented by the Environmental Footprint (EF) Method 3.0, which introduces a harmonized framework based on multiple environmental impact categories (e.g., climate change, ozone depletion, resource use [15].

1.3.2. First Phase; Goal & Scope Definitions

A fundamental parameter in any LCA study is the **goal and scope definition**, which establishes the **purpose** of the assessment and determines the extent of the system under analysis. Closely related to this is the definition of **system boundaries**, which specify which life cycle stages are included, such as cradle-to-gate, cradle-to-grave, or other boundary configurations. These choices directly influence the interpretation of results and their applicability to **decision-making** [13], [16]

The **reference study period** is another important element of the scope definition, particularly in building-related LCAs. For building systems, reference periods of approximately **50 years** have commonly been adopted to reflect typical building lifetimes and to capture long-term operational and replacement effects [13].

1.3.2.1. Functional unit

Across the literature, the **functional unit (FU)** is consistently highlighted as one of the most influential parameters in LCA. The functional unit provides a **quantified description of the system's function** and serves as the reference against which alternative systems or design options are compared [1]. In the context of HVAC systems, the choice of functional unit is particularly critical due to the **diversity** of system configurations and operating conditions [6], [17].

A wide range of functional units has been applied in previous HVAC-related LCA studies. These include **energy-based units** such as cooling or heating energy produced or consumed **(expressed in kWh, MJ, or kJ)**, **product-based units** such as a single air-conditioning or heating unit, and **spatial units** based on conditioned floor area or volume (m^2 or m^3) [6], [17]. This diversity reflects the absence of a universally accepted functional unit for HVAC systems and has been identified as a **key challenge** for comparability across studies [17].

In response to this lack of consensus, several sources recommend **energy-based functional units** that directly describe the delivered service. Suggested functional units include "**1 MJ of heat energy added to or removed from conditioned space**" or "**1 kJ of heat removal from the room space**," enabling consistent comparison of systems providing heating, cooling, or combined functions [6], [16], [17].

1.3.2.2. System Boundaries; LCA Modules

Life Cycle Assessment structures the evaluation of environmental impacts through a systematic division of the product or building life cycle into distinct stages. These stages allow impacts to be quantified consistently across different phases of production, use, and end-of-life, supporting transparency and comparability in environmental assessments [3], [5].

Across LCA studies, system boundaries are typically defined to include **upstream**, **use**, and **downstream** phases. Upstream processes encompass raw material extraction, manufacturing, and transportation. The use phase represents operational activities during the service life of the building or system, while downstream processes address end-of-life management, including landfilling, incineration, and recycling [17]. The selection of these boundaries determines which life cycle modules are included and directly influences the interpretation of LCA results.

Standardized life cycle modules for buildings

In the context of buildings and technical systems, life cycle stages are commonly defined according to the **EN 15978** framework. This standard divides the building life cycle into sequential modules that capture material-related, operational, and end-of-life impacts. The **product stage (A1–A3)** includes raw material extraction, material processing, and manufacturing of building products and technical equipment. The **construction stage (A4–A5)** covers transportation of products to the construction site and on-site installation activities. During the use phase, the **replacement module (B4)** accounts for periodic replacement of components over the building's service life, while **operational energy use module (B6)** represents energy consumed during building operation, including heating and other technical services. The **end-of-life stage (C1–C4)** includes deconstruction, transport of waste, waste processing, and final disposal[6].

These modules provide a structured basis for distinguishing between embodied impacts—primarily associated with product, construction, and replacement stages—and operational impacts linked to energy use during the building's use phase[5], [6].

Product-level modules and Environmental Product Declarations

For construction products and technical equipment, Environmental Product Declarations follow the EN 15804 standard and EN 50693, which defines a modular life cycle structure aligned with building-level assessment frameworks. Within this standard, modules **A1–A3** cover raw material supply, transport, and manufacturing of products. The **B4 module** captures the environmental impacts associated with replacement of components throughout the building's lifetime, while **B6** represents operational energy use related to the function of technical systems [5]. This modular structure enables consistent aggregation of product-level data into building-level LCA results.

Modules A1-A3; Raw Materials, Extraction, Production

Module A1-A3 encompasses all activities from the extraction of raw materials through to the completion of the finished product. It is specifically broken down into three sub-modules:

- **A1: Raw Material Supply:** This includes the extraction and initial production of the raw materials required for the system. For example, in studies of condensing boilers and heat pumps, this covers the supply of metals like copper, aluminum, and steel, as well as electronic components.
- **A2: Transport:** This refers to the transportation of raw materials or components to the manufacturing site.
- **A3: Manufacturing/Assembling:** This involves the actual production process, which includes energy and water consumption, welding, waste management, and the packaging of the final product [7], [9], [15], [18].

Module B4; Maintenance, Replacement

Within Life Cycle Assessment, maintenance and replacement activities are addressed during the use stage and are particularly relevant for technical building systems due to their limited service life compared to the overall building lifespan. The environmental relevance of these activities is primarily governed by the Estimated Service Life (ESL) of components, which determines the frequency of maintenance interventions and the need for replacement over time [5], [13].

Several sources indicate that routine maintenance activities generally have a limited influence on total life-cycle environmental impacts. Maintenance-related contributions, including the transportation of maintenance personnel, are reported to account for less than 5% of total environmental impacts in typical assessments. As a result, maintenance is often considered a marginal contributor in comparison to other life-cycle stages [2]. In some studies, maintenance impacts are not explicitly quantified, as they are expected to have a limited effect on overall environmental trade-offs between alternative systems [3].

In contrast, component replacement is consistently identified as a critical contributor to environmental impacts in the life cycle of technical installations. Replacement activities require the production, transport, and installation of new materials, thereby generating additional embodied emissions. Due to the relatively short ESL of technical equipment compared to the building envelope, multiple replacement cycles are typically included within LCA studies, commonly assuming building lifespans of 60 or more years [2], [5].

Quantitative findings from the literature highlight the significance of replacement-related impacts. The replacement stage (module B4) has been reported to account for approximately 36–64% of total embodied environmental impacts associated with technical installations. This substantial contribution reflects the cumulative effect of repeated component replacement over the building life cycle [3]. Consequently, the replacement stage plays a central role in determining the overall embodied impact of heating and ventilation systems.

Module B6; Operational emissions

Module B6 is defined and explained as the **"Operational energy use"** stage within the Life Cycle Assessment (LCA) framework. This module is part of the "Use stage" (Modules B1–B7) of a product or building's life cycle, specifically following the modular structure of the **EN 15978** standard [7]

Life Cycle Assessment distinguishes between **embodied** and **operational** emissions in order to capture the full environmental impact of buildings and their technical systems. Embodied energy refers to the total energy consumed during the production, transportation, and assembly of a system, including material extraction, manufacturing, and installation processes [1]. Operational energy use, by contrast, arise during the use phase of the building and are primarily associated with energy consumption for heating, hot water, and other services, this includes the consumption of **electricity, natural gas, and hydrogen** and environmental burdens of energy carrier extraction, distribution, and combustion (where applicable) within this module [18]

Module B6 is consistently identified as the **most significant phase** of the life cycle for residential heating appliances. It typically contributes to **over 90%** of the total environmental profile. For instance, in one study of a renovated building, the use phase (B6) accounted for approximately **88% to 92%** of the overall impact across different technologies [7]

1.3.3. Second Phase; Life Cycle Inventory and Data Quality Determinants

The **Life Cycle Inventory (LCI)** is the second phase of a Life Cycle Assessment (LCA), following the definition of goal and scope. It involves the detailed **compilation and quantification of inputs and outputs** specifically exchanges with the "Technosphere" and "Nature" for a product or system throughout its entire life cycle [7], [15]

The LCI phase is the stage where researchers collect data on **materials, energy inputs, and emissions** associated with each life cycle stage, from raw material extraction to end-of-life. For example, in the study of heating systems, the LCI includes specific data on the mass of components (e.g., copper, steel, aluminum), energy and water consumed during manufacturing, and emissions generated during the use phase [15]

The LCI serves as the foundation for the subsequent **Life Cycle Impact Assessment (LCIA)**, providing the raw data that will be converted into environmental impacts like climate change or toxicity [9]

Several key parameters and methodological choices can significantly influence the results of the inventory analysis. This could be the choice of modeling framework which could be Attributional or consequential as described before. Other than that, the accuracy of the LCI depends on the **activity data collected** (e.g., the exact amount of steel in a boiler) and the **secondary datasets** used to represent background processes like electricity generation. System Boundaries also determine what is included or excluded and Uncertainty considering an incomplete state of knowledge could effect the results [7], [15]

1.3.4. Third Phase; Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is a key phase of the Life Cycle Assessment (LCA) methodology, in which the data collected during the Life Cycle Inventory (LCI), such as material inputs and emissions, are translated into potential environmental impacts. This phase enables a comprehensive evaluation of the environmental performance of systems, materials, and buildings across their life cycle [15]

1.3.4.1. LCIA Framework and Steps

The LCIA process consists of several structured steps that progressively transform inventory data into environmental impact indicators:

- **Classification**: Emissions and resource uses are assigned to specific environmental impact categories, such as climate change, human toxicity, ecotoxicity, and resource use.
- **Midpoint Characterization**: Emissions are quantified and aggregated into midpoint impact categories using characterization factors. This step evaluates impacts at an intermediate stage of the cause–effect chain.

- **Damage Characterization (Endpoint)**: Midpoint impact categories are further aggregated into broader damage categories, such as impacts on human health, ecosystem quality, and resource availability.
- **Normalization**: Results may be expressed relative to a reference (e.g., total global impacts) to indicate the contribution of the studied system within each impact category.
- **Weighting**: Impact categories are assigned relative importance and can be aggregated into a single score, enabling comparison between alternatives.

The LCIA in this context is based on a **midpoint approach**, where environmental impacts are assessed at an intermediate level of the cause–effect chain. This allows a detailed evaluation of specific environmental themes such as global warming and resource use.

According to the applied methodology, the impact assessment **stops at midpoint characterization**, meaning that endpoint (damage) assessment and weighting are not always included in the final reported results.

In the applied framework, environmental impacts are organized into **midpoint impact categories** defined by the European Commission, including climate change, ozone depletion, acidification, and resource use. In many studies, climate-related indicators such as GWP receive particular attention; however, the literature consistently emphasizes the importance of considering a wider set of impact categories to avoid incomplete or misleading conclusions[13].

1.3.4.2. Characterization Methods

The conversion of LCI results into LCIA indicators is performed using characterization methods. Two methods are:

- **EF Method 3.1**, developed by the European Commission, is used to evaluate impacts across the 16 categories.
- **ReCiPe 2016**, an alternative method, generally used to test the robustness of the results.

Both methods quantify environmental impacts, although differences in characterization models lead to variations in certain impact categories, particularly toxicity-related indicators.

In this study, the **EF Method 3.1** is adopted due to its alignment with European regulatory frameworks. It provides a standardized set of impact categories and characterization models for environmental assessment.

Within the construction sector, **EN 15804 +A2 (2019)** adopts the EF 3.1 characterization method for Environmental Product Declarations (EPDs). However, in this framework, the optional steps of normalization and weighting are excluded, and results are reported at the midpoint level.

1.3.4.3. Trade-offs between impact categories

Several studies highlight that heating and HVAC systems exhibit different environmental performances across impact categories, leading to **significant trade-offs when evaluated through Life Cycle Impact Assessment**. These trade-offs arise from the underlying physical and operational characteristics of systems, including electricity consumption, refrigerant use, and material composition. For example, heat pump systems can reduce greenhouse gas emissions associated with fossil fuel combustion but may result in

higher impacts in ozone layer depletion associated with the production and manufacturing of refrigerants and in terrestrial ecotoxicity due to electricity consumption [2]. Similarly, natural gas boilers may show lower impacts in certain categories, such as human health, while exhibiting higher overall environmental burdens when multiple impact categories are considered [1]. Quantitative evidence further demonstrates this complexity in hybrid systems, where **reductions in greenhouse gas emissions of approximately 30%** compared to conventional gas boilers can be accompanied by **three- to six-fold increases in impacts such as human toxicity, water depletion, and metal depletion** [12]. At the component level, substantial differences are also observed, as specific technical systems contribute unevenly across categories; for instance, air handling units have been reported to contribute significantly more to freshwater ecotoxicity (approximately 59.3%) than to marine eutrophication (approximately 18.7%), and ventilation systems may contribute more to non-climate impact categories than to climate-related indicators [5]. Furthermore, technical installations can dominate specific impact categories, such as ozone depletion potential, accounting for up to 96% of total impacts, **primarily due to the embodied impacts of refrigerant production**, while in weighted or aggregated assessments, materials such as **copper and brass emerge as major contributors** due to their high environmental intensity across multiple categories [3]. These findings demonstrate that **reliance on a single indicator, such as global warming potential, can lead to misleading conclusions**, as systems with relatively low climate impacts may still generate disproportionately high impacts in categories such as acidification or eutrophication due to material use and processing routes [13].

1.3.4.4. Reporting and comparability

At the building scale, Life Cycle Assessment (LCA) results are typically normalized using spatial units, most commonly expressed as kilograms of CO_2-equivalent per square meter of floor area (kg CO_2-eq/m^2). This approach enables comparison between buildings of different sizes and configurations and allows aggregation of impacts from structural elements and technical systems. However, this type of normalization is mainly suitable for whole-building assessments and may not accurately represent the performance of individual components [1], [13].

When focusing on building components, such as heating emission and distribution systems, comparability should be based on the service provided. In this case, the Functional Unit (FU) is defined as **1 kWh of thermal energy (kWh_{th}) delivered** for space heating and domestic hot water. This allows consistent comparison between systems with different efficiencies and energy sources [7]

To simplify comparisons across multiple impact categories, results can be aggregated into a single environmental score. This process involves **normalizing** the results to a common scale and applying **weighting factors** that reflect the relative importance of different environmental impacts. The final result is expressed in points (**$\mu Pt/kWh_{th}$**), where a lower value represents a reduced overall environmental burden.

Therefore, while building-level assessments rely on spatial indicators (e.g., m^2), **component-level LCA requires a service-based functional unit**, ensuring that comparisons are made on the basis of equivalent thermal energy delivered rather than building size [7]

1.4. Assessment needs and literature gaps in the LCA of heating emission and distribution systems

Life Cycle Assessment (LCA) has been extensively applied in the evaluation of building energy systems, providing a comprehensive framework for quantifying environmental impacts across the entire life cycle of buildings and their technical components. In recent years, a growing body of literature has focused on understanding the environmental performance of heating systems within this framework, particularly in the context of decarbonization and energy efficiency targets. However, the scope and focus of these studies vary significantly, with a predominant emphasis on building-level assessments and heat generation technologies. As a result, certain system components especially emission and distribution systems have received comparatively limited attention, despite their potential contribution to both embodied and operational impacts. This section critically reviews the existing literature to identify key trends, highlight limitations in current approaches, and establish the need for a more detailed and component-level assessment of heating emission and distribution systems within LCA studies.

1.4.1. General Focus: Building-Level and Generation Systems

Historically, the operational phase has been identified as the dominant contributor to environmental impacts in building-related LCAs. For heating systems, impacts related to fuel combustion and electricity generation account for the majority of contributions to climate change and fossil resource depletion [2], [12]. In conventional grid-connected systems, the operation phase contributes between 80% and 100% of total Global Warming Potential (GWP) [6]. Operational energy use has been reported to represent approximately 37% to 60% of total life-cycle impacts, for instance, in case studies of EPBD-compliant dwellings [3].

Within these operational emissions, the focus is largely on generation technologies. For air-source heat pump systems, electricity consumption represents roughly 84% of operational emissions, with refrigerant leakage adding 13.8% [19]. In contrast, centralized hot water radiator systems rely on externally generated heat (such as CHP units), where the use phase accounts for more than 98% of total life-cycle greenhouse gas emissions [19]. Because these generation systems—driven by climate and energy carriers—historically dominate the profile, they remain the primary focus of recent literature.

1.4.2. Importance of Generation Systems via Climate and Operation

The reason generation systems are prioritized is their direct link to climate-dependent operational emissions. Research demonstrates a close correlation between heating demand and the climatic context; for example, in Mediterranean regions like Greece, solar availability and cooling demand are major factors [1]. In Northern Italy (Milan), climate change is projected to reduce heating demand by 30% while increasing cooling demand by over 200%, significantly altering energy performance due to the higher primary energy factor of electricity [20]. Evidence from colder climates like the Netherlands further confirms that reducing heating demand is the most effective strategy for lowering environmental impacts [2]. Consequently, identical technical systems demonstrate varying life-cycle profiles depending on geographic context and building-specific exposure, such as an apartment's position beneath a roof or its number of external walls [1] [2].

1.4.3. Embodied Emissions and Material Intensity

Despite this historical focus on operation, a shift is occurring. As buildings move toward higher energy efficiency, embodied emissions associated with production and construction become increasingly significant [1], [3], [5]. In highly energy-efficient buildings, embodied and operational impacts can approach similar magnitudes [3].

This transition highlights a critical trade-off: improvements in operational performance are often achieved through increased material intensity [2], [21]. Heat pump systems, for example, require up to ten times more material resources than conventional boilers, and advanced systems like ground-source heat pumps (GSHP) involve extensive installation processes and infrastructure [2], [21]. While the use phase may still account for 95% of total emissions in some recent heat pump findings, the production phase contributes approximately 50% of total impacts in categories such as metal depletion and human toxicity [12], [21].

1.4.4. Emission and Distribution Systems

This material importance extends directly to emission and distribution systems—radiators, floor heating, fan coils, piping, and ductwork. These components are often highly material-intensive and play a decisive role in determining environmental performance [2], [5], [13]. Heating systems are composed of various metals (copper, steel, stainless steel, aluminium, cast iron) and polymers (PVC, ABS, HDPE, PE) [12], [19], [22].

The impact is often disproportionate to mass. For example, brass valves can represent 9–36% of a system's embodied impact while being only 2% of its weight [3]. In radiator systems, copper pipes can exhibit impacts three times higher than steel [11]. Furthermore, ventilation systems are notably material-intensive, dominated by galvanized steel but also involving aluminium, EPDM rubber, and stone wool [5]. The role of recycling and eco-design is also critical; for instance, recycled aluminium requires only 8.1 MJ/kg compared to 207 MJ/kg for virgin material, and extending the service life of these components reduces the cumulative embodied emissions associated with replacement cycles [2], [19], [22].

1.4.5. The Literature Gap and Need for Comprehensive Analysis

To have a truly comprehensive assessment of HVAC systems and designs, it is essential to include these emission and distribution networks within LCA boundaries. Distribution efficiency, affected by pipe length and heat transfer coefficients, influences both energy losses and system sizing [19]. In duct-based systems, capturing the interaction between material use (duct size) and operational energy (pressure losses) is essential for a balanced assessment [5].

Embodied impacts from these non-generative components can range from 22% to 91% of total embodied impacts [3]. However, many simplified LCA approaches still exclude technical building equipment like pipes and ducts, which constitutes a major limitation and leads to a systematic underestimation of total impacts [5], [13]. While some studies emphasize that all components, from generation to control systems, collectively influence performance, there is a clear gap in recent literature regarding the isolated and detailed assessment of emission and distribution systems [16]. Addressing this gap is essential for developing generic guidelines and achieving long-term decarbonization goals [3].

The preceding analysis highlights a clear imbalance in the current body of literature, where the majority of studies prioritize building-level assessments and generation technologies, while emission and distribution systems remain comparatively underexplored. To further examine how these aspects are addressed in existing research, the following table provides a structured overview of selected studies, summarizing the technical systems assessed alongside the corresponding LCA modelling approaches and system boundaries. This synthesis enables a systematic comparison of recent literature, offering insight into prevailing methodological choices and revealing the extent to which emission and distribution systems are incorporated within life cycle assessment frameworks.

Author		Technical system	Region	LCA approach	LCI modeling
Emission, distribution and generation heating systems					
Zheng et al.	[19]	Air-source heat pumps, Steam/hot water radiator heating systems,	China	Attributional	Process-based
Rodríguez et al.	[23]	The study worked on a traditional copper finned-tube heat exchanger and a newly developed condensing stainless steel heat exchanger with a spiral pipe design.	Europe	Attributional	Process-based
Matjaz Prek.	[24]	Radiator heating (using steel or aluminium), floor heating (using polyethylene or polybuten), and fan coil convector systems.	Europe	Attributional	Process-based
Anastaselos et al.	[1]	The paper worked on oil and gas fired boilers, split unit air conditioners, mono-Si and poly-Si PV arrays, flat plate and evacuated tube solar thermal collectors, radiators, floor heating, copper pipelines, and hot water tanks	Greece	Attributional	Process-based
Inge Blom et al.	[2]	Individual non-condensing boilers, high-efficiency condensing boilers, exhaust air heat pumps, collective mechanical exhaust ventilation, balanced ventilation with heat recovery, and associated distribution networks including steel or plastic piping and radiators	The Netherlands	-	Process-based
Building heating generation systems					
Herrando et al.	[25]	Hybrid photovoltaic-thermal (PV-T) collectors integrated with air-to-water reversible heat pump (rev-HP), compared to conventional photovoltaic (PV) system and grid-based system	spain	Attributional	Process-based
. Miralles et al.	[26]	Heat pump and biomass boiler	spain	-	Process-based & input-output databases
Naumann et al.	[27]	Air-source heat pump (ASHP) and condensing gas boiler	Germany	Attributional and consequential	Process-based
Vivian et al.	[28]	Natural gas (NG) hot water heating system and solar heating (SH) system complemented with electricity	Brazil	-	Process-based

Famiglietti et al.	[7]	Condensing boiler, gas absorption heat pump, electric heat pump	Europe	Consequential	Process-based
Famiglietti et al.	[15]	Condensing boiler, gas-driven absorption heat pump	Europe	Attributional	Process-based
Yang et al.	[22]	A hot water heating (HWH) system with mechanical ventilation (including a heat recovery ventilator) and a forced air heating (FAH) system, using either electricity or natural gas	Montreal, Quebec, Canada	Attributional	Process-based-input-output
Viral P et al.	[29]	Central natural gas furnace with central air-conditioning; natural gas-powered hydronic boiler with central air-conditioning; and electric air–air heat pump for both heating and cooling.	United States	Attributional	Process-based
Lin et al.	[12]	The paper evaluates condensing gas boilers and hybrid heat pumps, which combine a gas boiler with an air-source heat pump.	United Kingdom	Attributional	Process-based
Whole-building technical installations					
Decorte et al.	[3]	Heating systems (condensing gas boiler, brine-water heat pump, and air-water heat pump) and ventilation systems (demand-controlled exhaust ventilation and balanced ventilation with heat recovery).	Flanders, Belgium	Attributional	Process-based
Passer et al.	[13]	Building fabric, finishing, and technical building equipment (including electrical installations, heating systems like gas and air-to-air heat pumps, solar heating, sanitary systems, and ventilation)	Austria	Attributional	Process-based
District heating / network systems					
Famiglietti et al.	[9]	Energy systems providing space heating (SH), space cooling (SC), and domestic hot water (DHW), including natural gas boilers, fuel oil boilers, LPG boilers, biomass boilers, electric-driven heat pumps, gas absorption heat pumps, gas engine heat pumps, solar thermal systems, district heating, and joule effect systems	Milan, Italy	Attributional	Process-based
Famiglietti et al.	[30]	The paper worked on 3rd and 4th generation district heating networks (including components like boilers, CHP plants, waste-to-energy plants, and solar thermal arrays) and groundwater-source vapor compression heat pumps	Milan, Italy	Attributional	Process-based

Mahon et al.	[31]	Waste heat-fed heat pump district heating system , biomass CHP plant district heating system , and individual gas boiler system	Ireland	-	Process-based
Famiglietti et al.	[32]	Fourteen social housing buildings, a fifth-generation district heating and cooling (DHC) network, groundwater large-scale heat pumps, building substations (with heat pumps and heat pump chillers), thermal storage tanks, and a 740 kWp photovoltaic solar array.	Milan, Italy	Attributional	Process-based
Cooling / ventilation focused systems					
Litardo et al.	[6]	The paper reviews studies on conventional grid-connected vapor-compression heat pumps and chillers, solar-powered AC systems, thermal-driven absorption and adsorption systems, ground source heat pumps, evaporative coolers, biomass heating/cooling systems, and thermoelectric cooling.	Europe, Asia, America	-	Process-based
Z. Zhou et al.	[33]	Heating sources: oil boiler, gas-fired cogeneration, ground source heat pump, coal cogeneration, gas boiler, absorption heating; cooling sources: air-cooled air conditioners, water-cooled air conditioners, conventional electric refrigeration air conditioners, GSHP (for cooling), absorption refrigeration; combination schemes including gas-fired cogeneration + conventional electric refrigeration and GSHP for both heating and cooling	Northern China cold regions	Attributional	Process-based
H. Bergsdal et al.	[5]	The paper worked on ventilation systems, specifically air handling units, circular and rectangular ductwork, and various fittings such as bends, saddles, T-pieces, reducers, fire dampers, flow dampers, silencers, and air diffusers.	Norway	Attributional	Process-based
Bordbaret al.	[16]	Vapor-compression air conditioning , inverter VAC, hybrid membrane-based air conditioning , solar HMBAC, desiccant enhanced evaporative air conditioning, and solar DEVap.	Persian Gulf region, Iran	Attributional	Process-based
Karkour et al.	[34]	Three residential air conditioner models with varying technologies, including inverters and different refrigerants .	Indonesia	-	Process-based

1.5. Novelty and Structure

As previously stated, this research focuses on assessing the environmental impacts of heating emission and distribution systems within a residential case study building. Based on the literature review presented in the previous section, it can be observed that the primary intention of this research is to examine these technical systems in depth from a Life Cycle Assessment (LCA) perspective. The aim is to compare different heating systems and to determine under which conditions each system may perform more sustainably.

The structure of this study is organized as follows. The research begins with the introduction of a residential apartment case study. The first technical phase consists of the design and energy modelling of the heating systems for this building. In this phase, three different heating emission systems are assessed and sized:

- Radiator system
- Radiant floor system
- Fan-coil system

All other variables of the building are kept constant in order to isolate the influence of the heating systems themselves. This allows for a clear comparison of energy consumption, required technical components, and associated system configurations.

The results obtained from the energy modelling phase provide the necessary input data for the second and central part of the study: the Life Cycle Assessment of the three heating systems. This phase evaluates and compares the environmental impacts associated with each system across defined life cycle stages. The final comparison is presented in the results chapter, where impact categories are analyzed and interpreted in detail.

The novelty of this research lies in its specific focus on heating emission and distribution systems. As identified in the literature review, most LCA studies in the building sector primarily concentrate on generation systems, such as heat pumps or boilers. In contrast, emission and distribution systems, such as pipes, manifolds, radiators, and embedded floor components, are often overlooked or treated as secondary elements. However, these systems also require significant material inputs and maintenance interventions, and therefore contribute to environmental burdens throughout the building life cycle.

By focusing on these components, this study aims to increase awareness during the design phase of buildings, particularly regarding technical system selection. Moreover, the results may support decision-making related to maintenance, replacement strategies, and long-term environmental performance during the service life of buildings.

Although this study has certain limitations, such as its dependence on a specific climatic context and assumptions within the energy modelling and LCA framework, it nevertheless contributes to improving understanding of the environmental implications associated with heating system selection. Highlighting these impacts is essential for promoting more informed and sustainable choices in building design and operation.

2. Materials and Methods

At this stage of the study, it is important to clarify that the research is based on a selected residential case study building located in Milan, Italy. The case study consists of a residential apartment used as the reference module for the assessment of different heating system configurations.

This chapter is structured into two main parts. The first part focuses on energy modelling, which represents the initial design phase of the HVAC systems. This phase begins with the introduction of the building characteristics, including climate location, orientation, geometry, and envelope components such as walls, windows, and assigned construction materials. Additional parameters such as apartment floor area, usage category, occupancy profile, operational schedules, and other relevant boundary conditions are defined to ensure accurate modelling.

One of the two primary software tools used in this research is IESVE, which is employed in this phase for dynamic building simulation. The software is used to model the building and to calculate the required heating energy demand under the specified conditions. Based on the simulation results, three different heating emission systems are designed and sized:

- Radiant floor system
- Radiator system
- Fan-coil system

For each configuration, the required number and specifications of components are determined in order to meet the heating demand in accordance with regulatory requirements. This includes sizing of emitters, distribution elements, and associated technical components.

The final output of the energy modelling phase consists of simulation results such as annual and seasonal heating energy demand, delivered and generated energy, generation system efficiency, and hourly or daily indoor temperature profiles. Indoor air temperature distribution and comfort-related parameters are also evaluated. These results provide a comprehensive understanding of the energy performance of the three HVAC configurations and form the basis for the next stage of the study.

The second and most central part of this chapter addresses the Life Cycle Assessment (LCA) of the designed heating systems. This part begins with the definition of the four standard LCA phases, starting with the goal and scope definition. The goal is to compare the environmental impacts of the three HVAC system configurations developed in the energy modelling phase. At this stage, detailed technical information is collected, including the number of components, material types, product specifications, and energy consumption over the service life of the building.

The next phase is the Life Cycle Inventory (LCI), in which all collected data are structured and quantified. The second primary software tool used in this research, SimaPro, is applied in this stage. Inventory data are entered into the software, and appropriate processes are selected based on the Ecoinvent database and the results obtained from the energy modelling phase. The system boundaries and assumptions defined in the goal and scope phase are consistently applied.

The final phase of this chapter is the interpretation, where results from LCIA are evaluated and comparioson is made between different modules and different systems, to identify hotspots and best performing system in the case study.

2.1. Energy modeling

The energy modeling stage of this work provides the analytical foundation required to evaluate and compare the environmental performance of three alternative HVAC emission systems—radiators, radiant floor heating, and fancoils—through Life Cycle Assessment (LCA). In order to enable a consistent and realistic comparison, a detailed building energy model was developed in IESVE for a representative residential apartment located in Milan, Italy. The model incorporates realistic construction assemblies, internal gains, occupancy patterns, ventilation schedules, and infiltration rates, in line with current regulatory requirements for near–NZEB buildings. The purpose of this phase is twofold: first, to characterize the apartment's heating energy demand through preliminary simulations; and second, to use these results to correctly size the emission systems, the associated hydronic networks, and the natural gas boiler for each configuration. By establishing the energy needs and operating profiles of the three HVAC setups, this section provides the necessary quantitative input for subsequent analysis of system efficiency, annual energy consumption, and ultimately, the life cycle impacts assessed in the later parts of the thesis.

2.1.1. Software Tools for Energy Modeling

For the energy modeling of the case-study apartment, the building simulation was conducted using the **IESVE** software platform, which integrates geometry, physics-based thermal simulation, HVAC design, and result–analysis tools in a unified environment[35].

A. IESVE and APACHE/ApacheSim

The core of the modeling work is based on the APACHE engine embedded in IESVE, which enables rigorous whole-building thermal performance and energy simulations.

- The APACHE application provides the user interface to set up the building model: define geometry, assign constructions (walls, floors, glazing), internal gains (occupancy, equipment, lighting), ventilation/infiltration parameters, and schedule profiles.
- The dynamic thermal simulation engine — referenced in IESVE as ApacheSim for load and energy computations — performs sub-hourly calculations of heat transfer (conduction, convection, radiation), thermal mass effects, solar gains, ventilation losses/gains, and other transient effects, using standard methods such as the ASHRAE heat-balance method among others.
- This approach ensures high fidelity in reproducing the building's thermal behavior on an hourly (or even finer) basis over the full year, capturing effects of occupancy, weather, internal gains, thermal mass and ventilation/infiltration as realistically as possible.

By using APACHE/ApacheSim, it is possible to obtain the building's baseline energy demand — heating loads — before specifying any HVAC system. This allows to size the emission systems and hydronic plant appropriately.

B. IESVE and ApacheHVAC Module

Once the building thermal demand is defined, the HVAC systems are modelled using ApacheHVAC, a module of IESVE designed for detailed, component-based HVAC system design, sizing, simulation and control.

- ApacheHVAC allows to assemble water-side and air-side plant loops, define emitters (radiators, radiant floor panels, fan coils), piping, boilers, pumps, control strategies, schedules, and other HVAC components.
- For each of the three configurations (radiator, radiant floor, fan coils), it is possible to create a separate HVAC network ("prototype HVAC network") tailored to that setup, sizing all components based on the building's computed load.
- During simulation, ApacheHVAC calculates the system's energy consumption, accounting for real operating conditions, distribution losses, control strategies and actual load profiles.

Thus, ApacheHVAC bridges the gap between theoretical building demand (as computed by ApacheSim) and realistic HVAC system behavior — a critical step for accurate estimation of energy consumption over the year, necessary for the comparative study.

C. VistaPro for Results Analysis

After running simulations (building loads and HVAC system operation), results are extracted and analyzed using VistaPro, the dedicated post-processing and reporting module within IESVE.

- VistaPro allows to visualize results at multiple levels: building-wide, zone/room-level, surface-level, or HVAC component-level; and to inspect variables such as heating energy consumption, internal/external gains and losses, system energy use, energy breakdown by source and end-use, hourly/monthly/annual summaries, and comfort indicators (if needed).
- Thanks to the integrated workflow, input data (geometry, constructions, gains, schedules, HVAC system definitions) and results remain consistent throughout the modeling process, reducing errors and ensuring traceability from assumptions to outputs.

2.1.2. Case Study Apartment

The case study for this study is a residential apartment located within a multi-family building in Milan, Italy. The selected floor plan consists of two adjacent apartments—one measuring **67.28 m²** and the other **83 m²**—separated by a **shared internal corridor** of approximately **40 m²**. The focus of this study is the **larger 83 m² apartment**, chosen for its representative size, suitability for near-NZEB energy performance requirements, and practical modeling feasibility in IESVE.

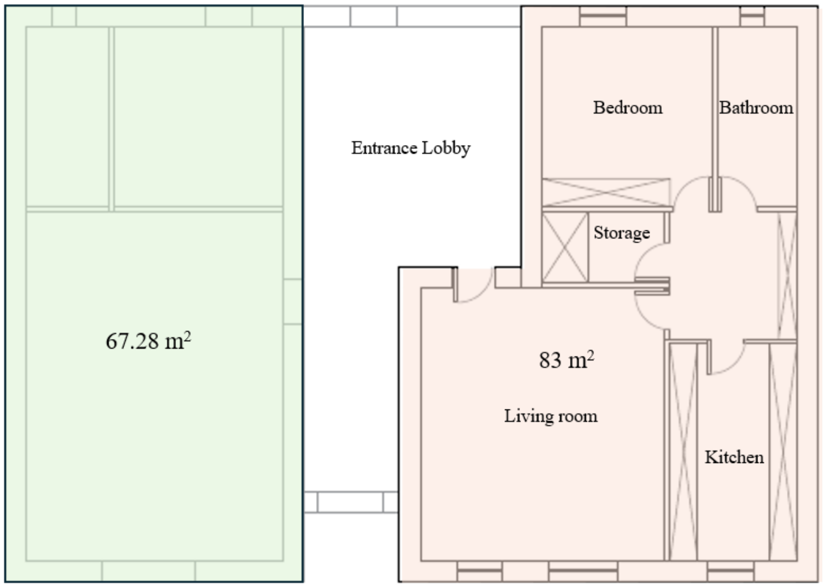

Figure 1: Building Floor Plan

The 83 m² apartment comprises a **living room**, **kitchen**, **bedroom**, **bathroom**, **storage room**, and an internal **connecting corridor**. The building plan also indicates the presence of **external doors and windows**, as well as fixed interior elements such as **built-in cabinets and shelving units**, which influence internal heat gains and available installation space for HVAC components. The apartment is bounded by three external façades facing **north**, **east**, and **south**, which results in different levels of solar exposure, thermal gains, and heat-loss characteristics across the envelope.

For the purposes of this research, the apartment is modelled with an **individual natural gas condensing boiler** dedicated exclusively to this dwelling. This assumption facilitates clear system-level comparisons between radiator, radiant floor, and fancoil configurations because it isolates the performance and energy consumption of each HVAC setup without interactions from neighboring units. Although this individual-boiler configuration is increasingly uncommon in newly constructed European buildings—where current regulations and policy trends, such as those embedded in the **EU Energy Performance of Buildings Directive (EPBD, recast 2018 and amendments 2023)**, encourage **centralised heating systems**, **shared heat generators**, and **low-carbon district-based solutions—**it remains appropriate for simulation-based system sizing, operational assessment, and LCA boundary control in the context of this study.

In the proposed layout, the condensing boiler is positioned inside a **wall-mounted cabinet** located along the **east external wall**, specifically within the corridor segment of the apartment. This area provides sufficient clearance and accessibility for the boiler while ensuring that the installation does not interfere with the main living spaces. Positioning the generator on an external façade also simplifies flue routing and combustion air requirements, making it a realistic engineering choice consistent with typical Italian residential practice.

The thermal performance of the building envelope plays a fundamental role in determining the heating demand of the apartment and, consequently, the sizing and operation of the HVAC systems evaluated in this study. For this reason, all opaque and transparent components were modelled in IESVE using realistic construction assemblies consistent with contemporary Italian residential practice and aligned with the performance requirements for near-NZEB buildings in the Lombardy region.

The building envelope consists of four primary opaque component types: **external wall**, **internal partition wall**, **roof slab**, and **internal floor slab**. Each assembly is composed of multiple layers, including structural materials, insulation layers, and finishing surfaces. For each layer, the physical and thermal properties—**thickness**, **thermal conductivity**, **volumetric mass**, **specific heat capacity**, and **thermal resistance**—were specified according to manufacturer data and standard material libraries. These properties were used by the APACHE simulation engine to compute transient heat transfer through the envelope, influencing internal temperatures, heating loads, and overall system operation.

Table **1** presents the detailed stratigraphy of the opaque components, including all material layers and their corresponding thermal properties. These constructions reflect realistic envelope performance levels for a recently built residential apartment in Milan while ensuring consistency with local minimum energy performance criteria.

Table 1: Detailed stratigraphy of the opaque components

							water vapor diffusion resistance factor in dry state
	External wall	mm	W/m.K	kg/m³	J/kg.K	m².K/W	
Layer	**Material**	**Thickness**	**Thermal Conductivity λ**	**Volumetric mass**	**specific heat capacity**	**thermal Resistance**	
-	resistance	-	-	-	-	0.13	-
1	plasterboard panels	13	0.25	900	1000	0.052	10
2	plasterboard panels	13	0.25	900	1000	0.052	10
3	Non-ventilated air cavity A< 500 mm²/m	10	0.0667	-	-	0.15	-
4	Glass wool panel (MUPAN 4+ type) thickness 40 mm	40	0.035	40	1030	1.143	1
5	Poroton600 hollow bricks (25.5 cm thick)	250	0.16	600	1000	1.563	6
6	Sintered expanded polystyrene (EPS with graphite)	160	0.031	20	1450	5.161	60
7	External plaster for thermal coat (e.g., decorative finish)	10	0.3	1300	840	0.033	30
-	resistance	-	-	-	-	0.065	-
	Internal wall						
-	resistance	-	-	-	-	0.13	-
1	plasterboard panels	13	0.25	900	1000	0.052	10
2	plasterboard panels	13	0.25	900	1000	0.052	10
3	Non-ventilated air cavity A< 500 mm²/m	15	0.0822	-	-	0.179	1
4	Glass wool panel MUPAN 4+ sp 60 mm	60	0.035	20	1030	1.714	1
5	plasterboard panels	13	0.25	900	1000	0.052	10
6	Non-ventilated air cavity A< 500 mm²/m	15	0.0822	-	-	0.179	1
7	Glass wool panel MUPAN 4+ sp 60 mm	60	0.035	20	1030	1.714	1
8	plasterboard panels	13	0.25	900	1000	0.052	10
9	plasterboard panels	13	0.25	900	1000	0.052	10
-	resistance	-	-	-	-	0.13	-
	Roof						
-	resistance	-	-	-	-	0.065	-
1	Ceramic tiles (tiles)	14	1.3	2300	840	0.011	-
2	Lightly ventilated air cavity Av = 600 mm²/m	60	-	-	-	-	-
3	Bituminous membrane (e.g., THERMO 2G)	1.8	0.17	1200	920	0.011	50000
4	Stiferite Class B (rigid polyurethane foam, sp 120–260)	120	0.025	44	1460	4.8	70
5	Vapor barrier in P.V.C. sheets	5	0.16	1390	900	0.031	50000
6	Calpestop 8 TNT (soundproofing mat with non-woven fabric)	8	0.037	30	1400	0.216	12918
7	LecaCem Mini (lightweight concrete with expanded clay)	100	0.142	600	1000	0.704	6
8	Distribution screed in concrete with mesh	40	1.49	2200	880	0.027	70
9	Hollow-core slab (reinforced concrete floor slab)	240	0.72	2000	1000	0.333	40
10	Non-ventilated air cavity A< 500 mm²/m	50	0.3125	-	-	0.16	-
11	Plasterboard panels	13	0.25	900	1000	0.052	10
-	resistance	-	-	-	-	0.1	-
	Internal slab						
-	resistance	-	-	-	-	0.17	-
1	Ceramic tiles (tiles)	14	1.3	2300	840	0.011	9999999
2	PaRis 2.0 (cementitious smoothing layer)	40	2.02	2000	1000	0.02	100
3	PaRis 2.0 (cementitious smoothing layer)	20	2.02	2000	1000	0.01	100
4	Expanded polystyrene (EPS) for SYSTEM VALTPLATTEN	30	0.035	30	1250	0.857	70
5	LecaCem Mini (lightweight concrete with expanded clay)	110	0.142	600	1000	0.775	6
6	Vapor barrier in PVC sheets	4	0.16	1390	900	0.025	50000
7	Expanded polystyrene for V-ESSE – V-ELLE 20/150	100	0.034	30	1300	2.941	70
8	Load distribution screed in reinforced concrete	40	1.49	2200	880	0.027	70
9	Reinforced concrete	220	1.49	2500	880	0.148	70
10	Gypsum plaster	10	0.4	1000	1000	0.025	10
-	resistance	-	-	-	-	0.17	-

Following the definition of material layers, the overall **thermal transmittance (U-value)** of each envelope component was calculated based on the sum of individual resistances and internal/external surface resistances. Table **2** summarizes the resulting U-values for all opaque components (external wall, internal wall, roof, internal slab, doors) as well as the transparent elements (windows). The table also reports the **total thickness** of each assembly.

Table 2: Opaque components total U-values

Component	Thickness (mm)	U-value ($W/m^2.K$)
External Wall	496	0.11
Internal Wall	215	0.23
Roof	651.8	0.15
Internal Slab	588	0.19
Windows [SHGC:0.499]	23	1.13
Door	37	2.3

The window system used in the apartment is characterized by double glazing with low-emissivity coating and thermally broken frames, providing a U-value consistent with current NZEB envelope performance standards.

These construction definitions were then assigned to each building surface in IESVE during the geometric modelling stage, ensuring that heat transfer, solar gains, thermal inertia, and envelope losses were all computed accurately during the dynamic simulations.

2.1.3. Input Data for Simulations

To ensure realistic dynamic energy simulations, a set of environmental, operational, and occupancy-related input data was defined in accordance with international standards and Italian regulatory requirements. These inputs govern the behavior of the building during the simulation period and directly influence the heating load, system sizing, and performance comparison of the three HVAC configurations.

2.1.3.1. Weather File and Climate Zone

The simulation uses the **Typical Meteorological Year (TMY)** weather file for **Milan Linate Airport (MIL_Linate.epw)**, which provides hourly climatic data including dry-bulb temperature, solar radiation, humidity, and wind speed. This file reflects representative long-term local climate conditions and is commonly used for building performance simulation studies.

According to the **ASHRAE Standard 169-2021**, Milan falls within **Climate Zone 4A**, characterized by mixed-humid conditions with significant seasonal temperature variations. Using a region-specific EPW file ensures that the heating energy demand and resulting HVAC performance reflect realistic meteorological conditions for northern Italy.

2.1.3.2. Internal Gains: Equipment Loads

Internal equipment gains were assigned to represent electrical appliances typically found in an Italian residential apartment (refrigerator, oven, TV, washing machine, lighting, etc.). A **maximum sensible gain of 332 W** was applied to the apartment based on aggregated appliance loads.

These gains were modulated through a **weekly schedule**, active **seven days a week**, with distinct hourly profiles reflecting typical residential usage patterns (higher in the morning and evening, reduced during working hours). The schedule applied follows general recommendations from residential occupancy and internal-gain schedules derived from **ASHRAE Standard 90.1 User Manual** and the **ASHRAE Fundamentals Handbook (2021)**. The detailed hourly distribution is shown in **Figure 2**.

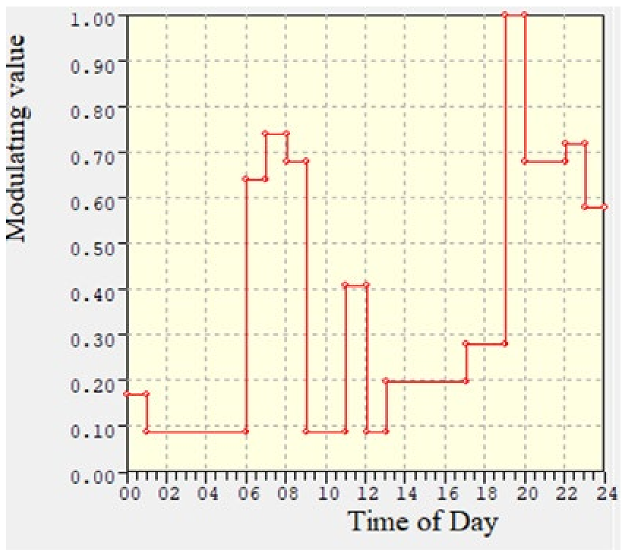

Figure 2: Hourly distribution of equipment load intensity

2.1.3.3. Internal Gains: Occupancy Loads

Occupancy-related internal gains were also incorporated according to recognized thermal comfort and metabolic standards. Each occupant was assigned:

- **60 W/person** sensible heat gain
- **40 W/person** latent heat gain

These values are consistent with metabolic heat generation for a **sedentary activity level (1.0–1.2 met)** as reported in the **ASHRAE Fundamentals Handbook (2021), Chapter 18 – Human Comfort and Thermal Balance**.

The apartment was modelled to represent a **four-person household**, distributed across a **weekly schedule** reflecting typical occupancy patterns (higher presence in mornings, evenings, and weekends). The occupancy schedule was implemented as an hourly varying profile for all days of the week, consistent with standard residential building modelling practices.

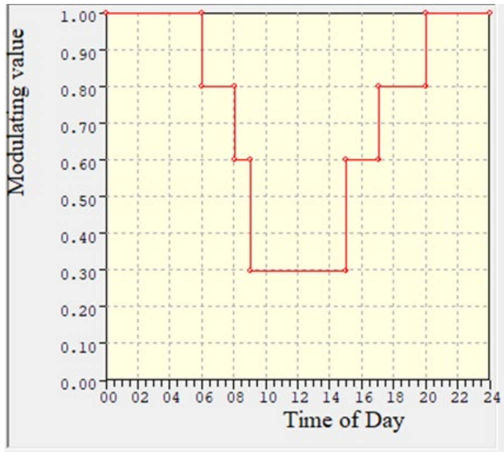

Figure 3: Hourly distribution of occupancy intensity

2.1.3.4. Air Exchange: Natural Ventilation and Infiltration Rates

Air exchange was represented through a combination of **background natural ventilation** and **infiltration**, both considered continuously active throughout the simulation period.

- **Natural ventilation: 0.10 ACH** (continuous outdoor air flow through window cracks and minimal window opening)
- **Infiltration: 0.08 ACH** (passive air leakage through the envelope)

The selected values fall within typical ranges for existing residential apartments and are consistent with guidance from:

- **UNI EN 16798-1:2019** (Indoor environmental input parameters)
- **ASHRAE Standard 62.1/62.2** (Ventilation for acceptable indoor air quality)

These air-exchange rates influence both ventilation heat losses and the heating load, especially during peak winter conditions.

2.1.3.5. Thermal Setpoints and Heating Operation Schedule

The indoor thermal setpoints were defined following typical comfort criteria for residential buildings:

- **Heating setpoint: 20 °C**
- **Cooling setpoint: 26 °C** (cooling is outside the scope of the present study and is therefore inactive in subsequent analysis)

Heating availability was scheduled according to the official Italian national regulations for residential heating operation. Under **Presidential Decree DPR 74/2013**, residential buildings in **Climatic Zone E**—which includes Milan—are permitted to operate heating systems from **15 October to 15 April**, for a maximum of **14 hours per day**, typically between **06:30 and 22:30**. These regulatory constraints were implemented directly in the heating schedule assigned to all conditioned zones.

2.1.4. Preliminary Results (Hourly Simulations with ApacheSim)

After defining all input parameters—including weather data, internal gains, occupancy schedules, ventilation/infiltration rates, operational schedules, and construction assemblies—a full-year **hourly dynamic energy simulation** was performed using the **ApacheSim** module of IESVE. This step is essential for characterizing the building's thermal behavior independently of any HVAC system configuration. By solving the transient heat balance for every hour of the year, ApacheSim provides a comprehensive breakdown of the **heat gains and losses** occurring through all envelope components and internal processes.

The purpose of this preliminary simulation is twofold. First, it quantifies the **heating load profile** of the apartment, indicating when and to what extent heating is required to maintain the comfort setpoint of 20 °C. Second, it decomposes the load into its physical contributors—**transmission losses**, **ventilation and infiltration losses**, **solar gains**, **internal gains**, and **inter-zonal gains**—allowing for a detailed understanding of how the building envelope, the climate, and occupancy patterns influence overall heating demand.

The results determine the **size and nominal capacity** of the emission systems (radiators, radiant floor, and fan coils), ensuring that each HVAC configuration is matched to the actual heating requirements of the dwelling.

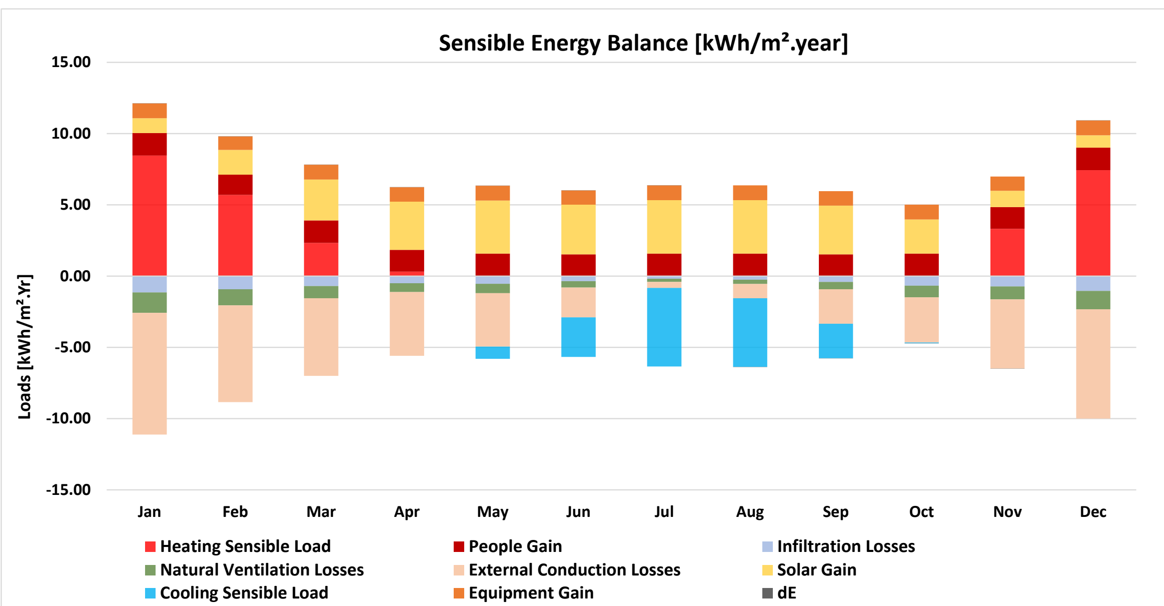

Figure 4: Preliminary Sensible energy balance results

Figure 4 illustrates the monthly **sensible energy balance** of the case-study apartment, expressed in kWh/m²·year, and decomposed into its primary contributing components. The results show clear seasonal trends typical of a residential building in Milan's **Climate Zone E**, with substantial **heating demand** during winter and shoulder months, and a predominance of internal and solar gains during summer.

During the coldest months, **January, February, and December**, the apartment experiences its highest **heating sensible loads**, driven primarily by **external conduction losses** through the building envelope and **infiltration/natural ventilation losses** associated with the 0.18 ACH combined air-exchange rate. Envelope-related losses are particularly pronounced in January, where the low outdoor temperatures result in a strong temperature gradient across the external walls and windows, making transmission heat loss the dominant contributor. Infiltration losses also become significant in winter, highlighting the sensitivity of the building to envelope tightness and natural ventilation assumptions.

In contrast, the internal gains from **occupants** and **equipment** remain relatively stable throughout the year, reflecting the constant occupancy and appliance-use profiles defined in the simulation inputs. Although modest in magnitude, these internal gains contribute positively to the winter energy balance by partially offsetting heating requirements. In summer months (June–September), internal gains combine with **solar gains** to increase the sensible load, but because cooling is outside the scope of this study, these positive loads are not mechanically mitigated by an active cooling system.

Solar gains exhibit a typical seasonal pattern, with higher contributions during **spring and summer**, but they remain moderate overall due to the building's façade orientations and window design. Their contribution in winter is beneficial, slightly reducing heating demand, especially during shoulder months such as March and October.

Overall, the sensible energy balance confirms that the apartment's heating needs are driven predominantly by **transmission heat losses** through the envelope and **air-exchange losses**, while internal and solar gains play a secondary but meaningful role in moderating winter loads. This decomposition is essential for understanding the relative influence of envelope performance and ventilation on the resulting HVAC system sizing and for anticipating how each emission system (radiators, radiant floor heating, or fancoils) may perform under varying seasonal conditions.

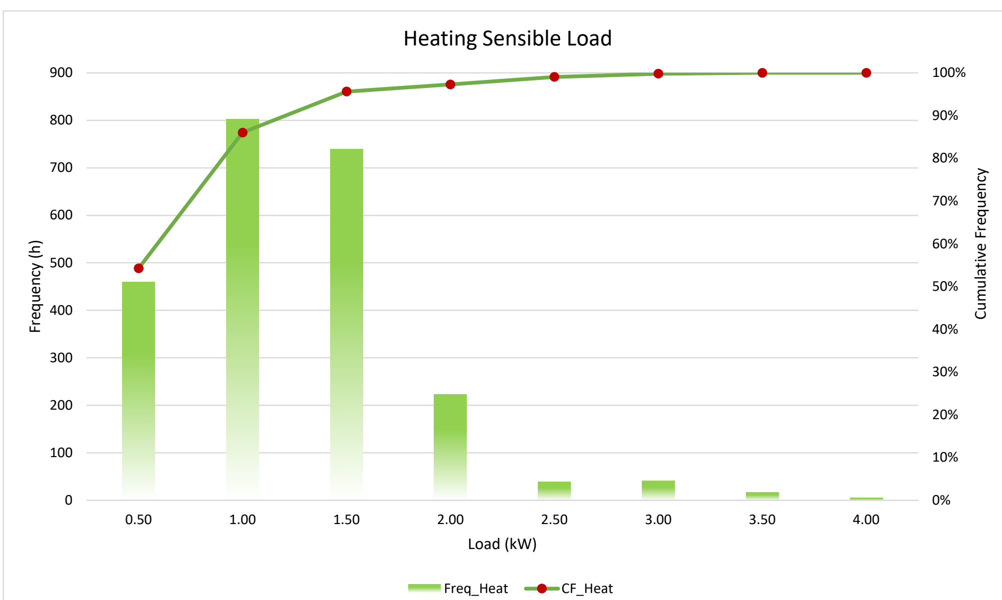

Figure 5: Frequency chart of heating sensible load

Table 3: Summary table of energy results

Parameter	Value	Unit
Area	83	m^2
Annual Heating Energy Needs	2288.81	kWh
Annual Heating Energy Needs per floor area	27.58	kWh/m^2
Peak Heating Load (15-16 Jan)	3.67	kW

To correctly size the HVAC emission systems and avoid unnecessary oversizing, the hourly heating loads obtained from the ApacheSim simulation were analysed through a **frequency distribution** (Figure 5) and a corresponding summary table (Table 3). The frequency chart illustrates how many hours of the year the building requires a given level of sensible heating load, while the cumulative frequency curve reveals the percentage of annual hours associated with each load bin.

The results show that the majority of heating demand occurs at relatively low to moderate loads. Specifically, loads between **0.5 kW and 1.5 kW** occur for more than half of the heating season, corresponding to typical winter days where the combination of envelope losses, infiltration, and internal gains results in moderate heating requirements. As the load increases, the frequency rapidly decreases: loads above **2.0 kW** occur for fewer than **10% of annual hours**, reflecting more extreme outdoor temperature conditions or periods with lower solar gains.

The cumulative frequency curve is particularly useful for system sizing. According to standard engineering practice and to ensure energy-efficient design, it is appropriate to select a heating system capacity that meets **98% of annual heating hours**, rather than sizing according to the absolute maximum peak load, which may occur only a few hours per year. Following this criterion, the cumulative curve identifies a **design sensible heating load of 2.5 kW**, which adequately covers 98% of the heating demand profile without oversizing the system.

Although the simulation recorded slightly higher peak loads—exceeding **3.0 to 3.5 kW**—these occur only during exceptionally cold conditions, specifically on **15 and 16 January**, representing a very small fraction of the total heating season. These peak values are still important, as they provide insight into periods of elevated stress on the HVAC system and help interpret performance later in the analysis. However, using them as the design basis would result in unnecessarily large emission systems and boilers, reducing energy efficiency and increasing installation costs.

By adopting **2.5 kW as the design heating capacity**, the study ensures that all three HVAC configurations (radiators, radiant floor heating, and fancoils) are sized consistently, realistically, and in line with good engineering practice. This approach also supports the later Life Cycle Assessment by avoiding oversized systems that would distort embodied and operational energy comparisons.

2.1.5. HVAC Configurations

The objective of modeling the three HVAC configurations is to evaluate the energy performance of different heat emission and distribution systems within the same residential apartment. The simulations aim to quantify how much energy is supplied by the boiler for each configuration, the operating hours of the boiler and circulation pump, and the corresponding supply and return water temperatures. Furthermore, the analysis investigates thermal losses along the distribution network, overall system efficiency, and indoor thermal comfort conditions, in order to identify which configuration delivers the most effective and energy-efficient heating performance.

The results obtained from these simulations also provide essential information for the subsequent Life Cycle Assessment (LCA). By quantifying the operating conditions—such as the temperature differences between generation and emission systems, operating hours, and total energy demand—it becomes possible to determine the amount and type of components and materials required to meet the heating needs of the case study apartment. These data are later used as input for the LCA phase to assess the environmental impact of each emission and distribution configuration.

To ensure comparability between the three HVAC models, several parameters were standardized. All configurations employ the same condensing boiler, circulation pump, and manifold system to distribute hot water to different zones. This approach allows the analysis to focus exclusively on the effects of emission and distribution system design rather than variations in generation efficiency.

Finally, it is important to note that the condensing boiler is modeled as being installed within the apartment unit itself. Although current Italian regulations recommend centralized generation systems for newly constructed buildings, many renovated buildings still utilize individual in-unit boilers. Adopting this configuration in the simulation allows for a more realistic assessment of typical renovation scenarios and facilitates a controlled comparison between the three emission systems under study.

In all configurations, the **heating operation schedule** was established in accordance with Italian regional regulations for the city of Milan, which permit heating from **October 15 to April 15**, for a maximum of **14 hours per day** between **6:00 a.m. and 10:00 p.m.** This schedule was implemented in the IESVE model for all HVAC configurations to ensure compliance with real operating conditions.

For the **control strategy**, a heating **setpoint temperature of 20 °C** was applied with a **deadband of ±1 °C**, resulting in an effective control range between **19 °C and 21 °C**. Accordingly, the system activates when the thermal zone temperature drops below 19 °C and switches off when it exceeds 21 °C. This control logic was uniformly implemented across all configurations to maintain consistency and comparability in system performance. The schematic below illustrates the control system setup as modeled in IESVE for the three heating configurations.

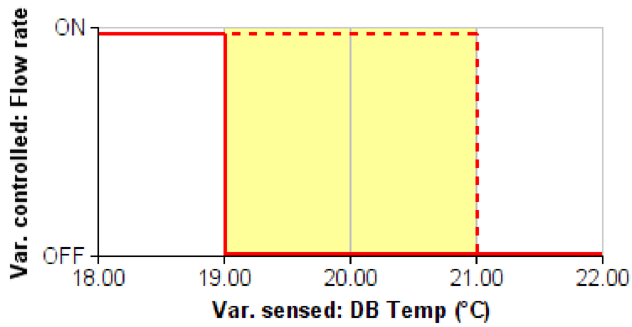

Figure 6: Temperature control system setup

This study evaluates three hydronic heat-emission systems representative of contemporary residential renovations: **radiators**, **radiant floor heating**, and **fan coil units**. Each system is modeled using a specific commercially available product and installed through a unified hydronic distribution network. The purpose of this section is to clarify the functional logic, construction characteristics, and selection rationale of the emitters and distribution elements before presenting the configuration-level modeling.

2.1.5.1. Overview of Modeled Emission and Distribution Systems

1) Radiators – Stelrad Classic Column (UIN 163019)

Radiators are convective–radiative terminal units in which heat is delivered by a warm water flow circulating through steel elements. In this work, the modeled radiator type is the *Stelrad Classic Column Horizontal*, a multi-column steel emitter designed for moderate to high operating temperatures. Its geometry provides a large external surface, enabling stable heat release through natural convection without mechanical airflow.

The selection of this radiator was motivated by its **representativeness of typical renovation scenarios** in Milan, where traditional wall-mounted radiators remain widely used. Its metal construction, column spacing, and certified performance under EN 442 testing ensure predictable behavior under low to medium water temperatures supplied by a condensing boiler. This configuration therefore serves as the benchmark "conventional" hydronic system in the analysis.

2) Radiant Floor Heating – Danfoss FH PEX-A 16×2.0 with EVOH Barrier

Radiant floor systems rely on low-temperature water circulating through embedded polymer pipes, transforming the entire floor slab into a large-area heat emitter. The system modeled here uses *Danfoss FH PEX-A 16×2.0 mm pipes*, featuring a five-layer structure with an EVOH anti-oxygen diffusion barrier. PEX-A provides excellent flexibility for loop installation and ensures long-term durability, while the EVOH layer prevents oxygen ingress, protecting metal components (valves, manifolds, boiler) from corrosion. This system was selected because it represents a **modern low-temperature solution** able to operate efficiently with condensing boilers, improve thermal comfort through uniform radiant heat, and match the construction typologies often encountered in deep energy retrofits.

3) Fan Coil Units – Carisma CRC13

Fan coil units deliver heat primarily by **forced convection**, using a finned heat exchanger coupled to a variable-speed fan. The modeled device is the *Carisma CRC13*, a compact wall/ceiling unit commonly used in residential spaces. FCUs are capable of rapid temperature response, strong air mixing, and compatibility with moderate water temperatures.

This unit was selected to represent a **dynamic, mixed-mode emitter** that combines heating and cooling potential and is suited for apartments where occupancy schedules vary or fast warm-up is required. Compared to radiators and radiant floors, FCUs rely more on air movement, providing a contrasting operational logic that enriches the comparative analysis.

4) Hydronic Distribution Piping

All three configurations share the same hydronic distribution approach, modeled using *Giacomini R999* multilayer pipes. R999 is a **PEX-b / aluminum / PEX-b composite pipe**, where:

- the **aluminum core** ensures shape stability, reduced thermal expansion, and a complete barrier against oxygen diffusion;
- the **inner and outer PEX-b layers** provide mechanical resistance, flexibility, and corrosion protection;
- multilayer bonding gives the pipe good crush resistance and long-term durability (EN ISO 21003).

The R999 range is suitable for both heating and cooling networks, supports typical boiler operating temperatures (up to ~95–100 °C), and offers low roughness for stable hydraulic behavior. The use of a multilayer pipe is particularly appropriate in apartment renovations because it facilitates:

- **straightforward installation** in constrained geometries,
- **mechanical stability** and controlled bending without spring-back,
- **hydraulic reliability** (low internal roughness, well-characterized pressure-drop curves),
- **oxygen-tightness**, preventing boiler and manifold corrosion.

In this thesis, R999 pipes define the primary distribution from the boiler to the manifold and the secondary branches supplying each emitter (for Radiators and Fancoils). Their standardized characteristics ensure that performance differences among the three modeled configurations arise from the **emission system**, not from the piping.

2.1.5.2. Configuration 1 – Radiator System

Radiator Calculations

Before implementing the radiator system model in IESVE, several preliminary calculations and data inputs were required. The design process began with the assessment of the building's heating energy needs, which were determined in the section 4. From the frequency chart of the sensible heating load, the maximum heating demand was found to be approximately 3.5 kW. To avoid oversizing the system, the value corresponding to the 98% frequent heating load, equal to 2.5 kW, was selected as the design reference. This value represents the hourly heating requirement of the apartment during the heating season.

Based on this design load, radiators were selected using technical data from the manufacturer Stelrad Radiator Group [36]. The chosen model is a classic horizontal column radiator (Stelrad UIN code *163019*), characterized by three columns, a nominal reference temperature of 50 °C, a rated heat output of 1135 W, and an *n*-coefficient of 1.25. The table below presents the preliminary input data for the radiators, obtained from the manufacturer's datasheet.

Table 4: Radiators general information

Stelrad UIN 163019		
Height	500	mm
Length	1042	mm
Elements	22	
Columns	3	
Weight	26.09	kg/m
Water Content	17.39	l/m
n-coefficients	1.25	
Heat Output	1135	W

For this configuration, a **supply temperature of 60 °C** and a **return temperature of 50 °C** were assumed for the boiler, while the **design ambient temperature** was set at **20 °C**, in accordance with Italian regulations and standard NZEB building design practices. Using the input data obtained from the radiator manufacturer's datasheet, it is important to account for the fact that the radiator's heat output varies depending on the supply and return water temperatures. Considering the reference temperature difference and the *n*-coefficient provided by the manufacturer, the formula below was applied to calculate the actual heat output of each radiator under the specific operating conditions of this study (supply, return, and ambient temperatures).

$$K_m = Q_{rad}(\Delta T_{ref})/(\Delta T_{ref})^n \quad (1)$$
$$\Delta T = T_s - T_a = ((T_{out} + T_{in})/2) - T_a \quad (2)$$
$$Q_{rad} = K_m * (T_s - T_a)^n \quad (3)$$

By dividing the total maximum heating demand of the apartment by the calculated heat output of a single radiator, the required number of radiators was determined. The final results are summarized in the table below, indicating a total of four radiators for the case study apartment.

Table 5: Calculated technical data of radiators

Reference Temperature Difference	ΔT_{ref}	50	˚C	Data Sheet
Heat output at the reference temperature	Q_{rad} (ΔT_{ref})	1135	W	Data Sheet
Coefficient	n	1.25	-	Data Sheet
Radiator Heat Emission Coefficient	K_m	8.54	W/˚C	Calculated
Inlet Water Temperature	$T_{w,in}$	60	˚C	Design Conditions
Outlet Water Temperature	$T_{w,out}$	50	˚C	Design Conditions
Inlet & Outlet mean Water Temperature	T_s	55	˚C	Calculated
Inlet and Outlet Water Temperature Difference	ΔT_w	10	˚C	Calculated
Ambient Temperature	T_a	20	˚C	Design Conditions
Ts-Ta	ΔT	35	˚C	Calculated
Each Radiator Heat Ouptput at Designed	Q_{rad}	726.72	W/rad	Calculated
Total Number of Radiators	n_{rad_tot}	4	-	Calculated

The radiator placement within the apartment followed standard design recommendations to minimize transmission losses and ensure uniform heat distribution. All radiators were positioned below windows, where the convective airflow helps counteract downdrafts and improve thermal comfort. The spatial layout of the radiators, boiler, and connecting pipe network is shown in Figure 7 (layout plan of the radiator configuration).

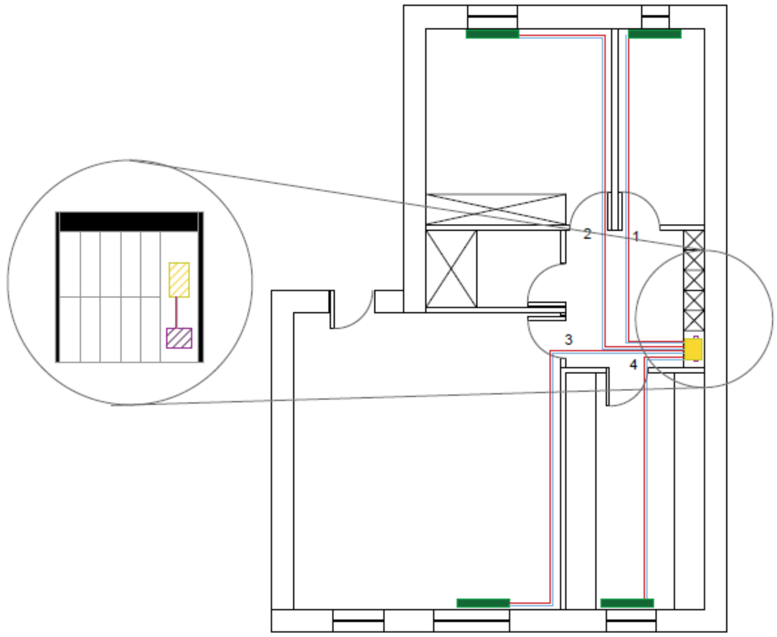

Figure 7: Radiator system layout plan

After determining the number and location of radiators, hydraulic calculations were performed to determine the required volumetric flow rate through the main supply pipe from the boiler to the manifold, as well as through the distribution branches connecting each radiator. The **mass flow rate for each radiator** was calculated using the first law of thermodynamics (energy balance), which relates the radiator's heat output to the specific heat capacity of water and the temperature difference between the supply and return flows.

$$Q = m_w * c_{p,water} * \Delta T_w \qquad (4)$$

By applying the calculated heat output of each radiator, the known specific heat capacity of water, and the 10 °C temperature difference (60 °C supply and 50 °C return), the corresponding mass flow rate for each radiator was obtained. Using these results and the manufacturer's data, the total mass flow rate per radiator and for the overall system was determined, as summarized in **Table 6**.

Table 6: Radiator system technical data

Radiator Weight per meter	wrad	26.09	kg/m	Data Sheet
Radiator Water Content per meter	cw_rad	17.39	l/m	Data Sheet
Radiator Length	l	1042	mm	Data Sheet
Radiator Weight	Wrad	27.19	kg	Calculated
Radiator Water Content	Cw_rad	18.12	l	Calculated
Radiator Heat Output	Qrad	726.72	W/rad	Calculated
Water Specific Heat	cp_water	4186	J/Kg.K	Resources
Inlet and Outlet Water Temperature Difference	ΔTw	10	˚C	Calculated
Water Mass flow Rate	mw_rad	0.017	kg/s	Calculated
Number of Radiators	nrad_tot	4		Calculated
Total Mass flow Rate	mw_tot	0.069	kg/s	Calculated

From the radiator performance chart shown below, and considering the **mass flow rate of each radiator equal to 61.2 L/h**, the **pressure drop per radiator** was estimated to be approximately **150 Pa**.

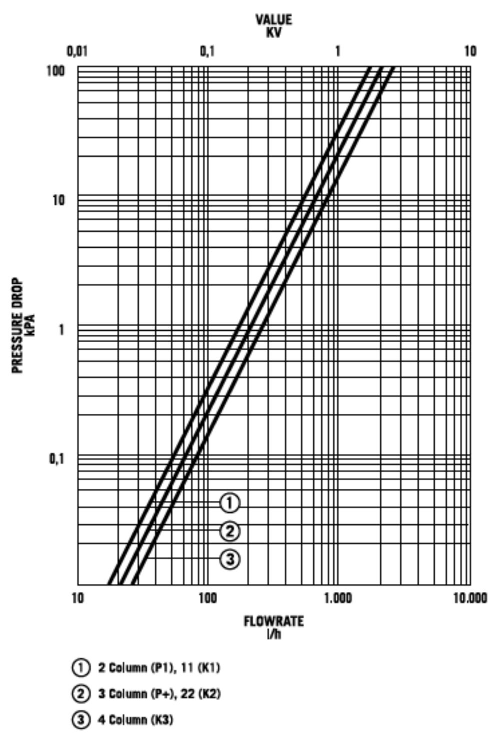

Figure 8: Pressure drops of radiators for each flow rate from technical datasheet

These calculated parameters were then implemented in the IESVE ApacheHVAC module to simulate the thermal performance, system efficiency, and energy consumption of the radiator-based heating configuration.

Hydronic Distribution System

In the design of the hydronic heating network for the apartment, two possible configurations were initially considered: 1) a main loop distribution with several branch joints (Right), and 2) a separate piping configuration in which each terminal unit (radiator) is connected directly to a central manifold through individual supply and return circuits (Left).

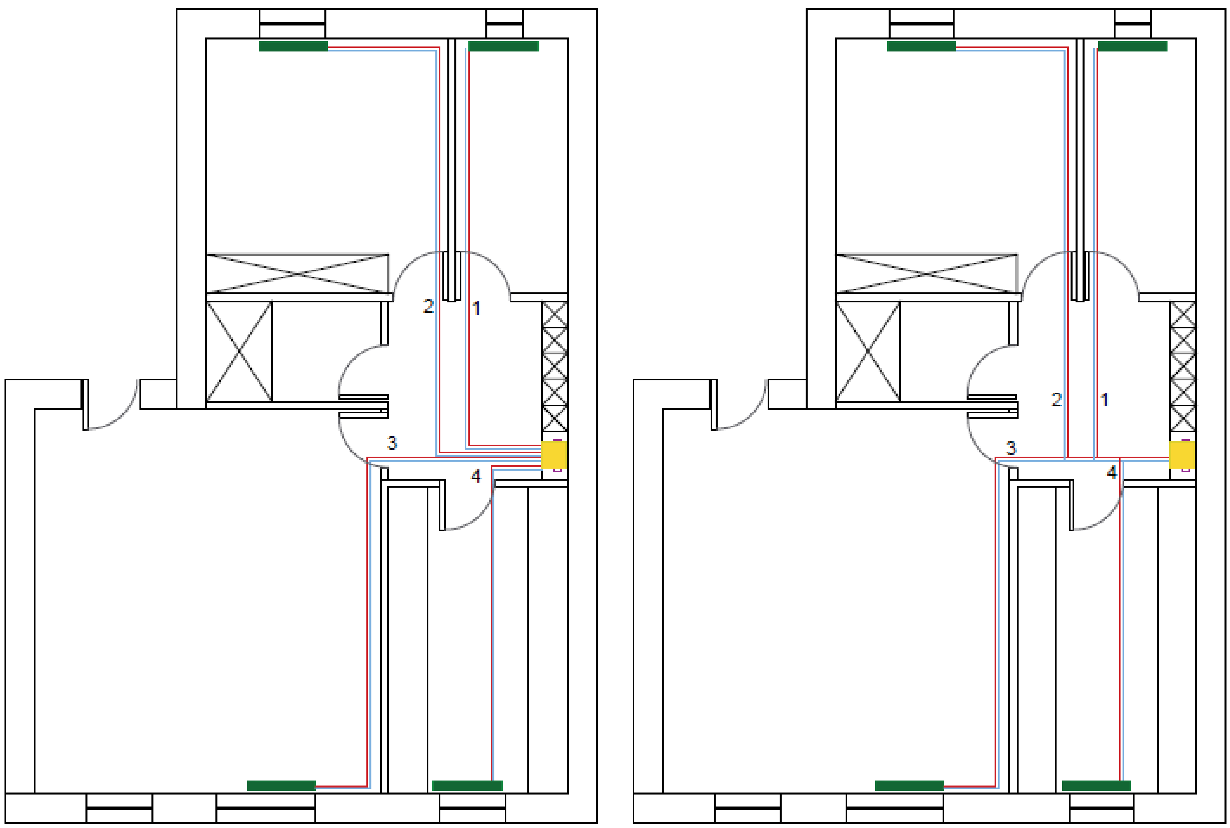

Figure 9: Different Distribution pipes layouts

After a preliminary technical assessment, the second solution was selected for the subsequent modeling and analysis, as it better complies with efficiency and regulatory requirements for modern residential buildings. The First loop configuration, although simpler and involving a lower total pipe length, presents several limitations such as uneven temperature distribution between emitters, more complex balancing requirements, and higher return water temperatures, which reduce the seasonal efficiency of condensing boilers. For these reasons, it was not developed further in this study. The adopted configuration (2) is based on a compact manifold assembly from which each radiator is served by a dedicated pair of pipes, ensuring stable hydraulic balance and uniform thermal distribution across all zones. Although this system requires a slightly higher material input, with approximately 20–30% longer total pipe runs and additional brass or steel components for the manifold and valves, it provides higher performance and operational flexibility. The design also facilitates integration with thermostatic valves and smart controls, enabling room-by-room temperature regulation and supporting low-temperature operation in accordance with UNI EN 12828:2015 — *Heating systems in buildings — Design for water-based heating systems* — which emphasizes hydraulic separation, balancing, and efficiency in closed water distribution networks.

From a life-cycle perspective, this approach is advantageous because the improved hydraulic control and reduced return temperatures contribute to higher boiler efficiency and lower annual energy consumption. Over the expected service life, the resulting operational energy savings outweigh the minor increase in embodied impact due to additional pipe material. Furthermore, the configuration aligns with NZEB (Nearly Zero Energy Building) principles widely adopted in recent residential renovations in Milan, supporting both technical performance optimization and environmental sustainability throughout the building's life cycle.

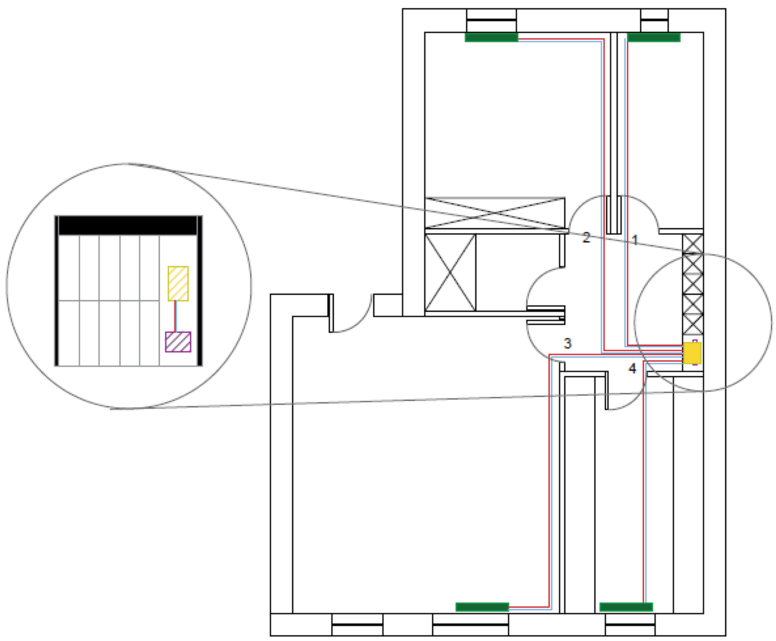

Figure 10: Selected distribution pipes layout

Once the radiators, volumetric flow rates, and pressure drops at the radiator level were determined, attention turned to the distribution system. The distribution network in this system consists of pipes connecting the boiler to the manifold and then from the manifold to the individual radiators. In the present configuration, both the boiler and manifold are mounted on the same wall, resulting in a pipe length of 0.6 meters for each supply and return leg. The pipes used for this distribution are of size **20×2 mm** (Giacomini R999 [37]), with a total volumetric flow rate of **0.069 L/s**. According to the manufacturer's data sheet, the linear pressure drop is **250 Pa/m**.

To minimize thermal losses, the pipes were insulated using **Giacomini R999** insulation with a thickness of **13 mm** and a total thermal conductivity of **0.04 W/m·K**. This allowed the calculation of the thermal transmittance of the pipes, which was found to be **0.198 W/m·K**. The calculated thermal loss or gain from the distribution pipes, as shown in the formula below, was taken into account. Since the entire distribution system is located within the thermal zone of the apartment, any heat loss from the pipes would contribute positively to the apartment's heating load. The inclusion of insulation helps reduce these losses and increase the operational efficiency of the radiators by maintaining appropriate working temperatures.

$$\Psi = \frac{\pi}{\frac{1}{2*\lambda}*\ln(\frac{D}{d})+\frac{1}{\alpha_{air}*D}} \text{ [W/m K]} \tag{5}$$

$$Q_{loss} = \psi * l * (T_{water} - T_{env}) * \Delta t \text{ [kWh/year]} \tag{6}$$

$$Loss\ fraction = \frac{Q_{loss}}{Q_{heat}} \text{ [\%]} \tag{7}$$

Where:

- d pipe external diameter [m],
- D thermal insulation external diameter [m],
- λ insulation thermal conductivity [W/m.K],
- α_{air} convective coefficient [W/m^2.K] = 4 W/m^2.K, when pipes are in internal environment,
- Ψ Linear thermal transmittance [W/m.K],
- l pipe length [m],
- T_{water} average water temperature [˚C],
- T_{env} average temperature of the environment in the heating season [˚C],
- Δt period of use of the heating system [h/year],
- Q_{heat} annual heating needs [kWh],
- Q_{loss} annual heat loss [kWh].

In the formula above, **α_{air}** represents the convective heat transfer coefficient, which for internal pipework located within the conditioned thermal zone is assumed to be **4 W/m²·K**. The parameter **T_{water}** corresponds to the mean temperature of the supply and return water, while **T_{env}** denotes the ambient environment temperature, taken as the **design indoor temperature of 20 °C**. The term **Δt** represents the total number of operating hours per year during which the radiator system is active. Based on the simulation results from **IESVE ApacheHVAC**, the radiator system operates for approximately **920 hours** over the heating season.

For the piping system from the manifold to the radiators, **Giacomini R999 16×2 mm** pipes were chosen, with a volumetric flow rate of **0.017 L/s** per circuit. The pressure drop per meter of these pipes is **70 Pa**, and the insulation is **10 mm** thick, with the same thermal conductivity as the main distribution pipes. The calculated thermal loss or gain from this section of the system was also considered, as shown in the table 7. It is worth nothing that, piping system is placed inside the thermal zone and even though each heat loss through the pipes would contribute to heat gain of thermal zone, the purpose of insulation instalment is for maintaining supply water temperature for radiators, for an efficient system working.

Table 7: Radiator system pipe circuits thermal data

	mass flow rate	linear thermal transmittance	Length	heating energy gain to the thermal zone	pipes pressure drop
	m_w (kg/s)	Ψ (W/m.K)	Length (m)	Q_{gain} (kWh/Yr)	Δp (Pa)
main pipe (boiler to manifold)	0.069	0.198	1.2	6.20	300
circuit 1 (manifold to radiator)	0.017	0.184	14.36	68.88	1005.2
circuit 2 (manifold to radiator)	0.017	0.184	18.94	90.84	1325.8
circuit 3 (manifold to radiator)	0.017	0.184	16.98	81.44	1188.6
circuit 4 (manifold to radiator)	0.017	0.184	11.2	53.72	784

It is also worth noting that, in line with IESVE modeling practices, distribution losses within the apartment are considered to be **0%**, since the entire piping system is contained within the thermal zone. This simplification, as referenced in the IESVE help documentation, assumes that any heat loss from the distribution network would be beneficial to the thermal performance of the apartment. However, to enhance the precision of the model, an additional consideration was made for the **main pipe segment** connecting the boiler to the manifold. This section, mounted along the internal corridor on the external wall, was modeled with a **loss fraction of 0.27%**. Although this value is very small, it was included to account for the minor heat exchange with the external envelope and to improve the overall accuracy of the energy model.

To conclude the **pressure drop calculation**, in addition to the pipe pressure losses, the pressure drops across the **manifold, thermostatic valves, and joints** must also be considered. For this case, the selected manifold is manufactured by **Caleffi**, model **"Collettore di distribuzione per impianti di riscaldamento, Serie 662** [38]**,"** featuring **four circuits** corresponding to the number of radiator branches. Taking these additional components into account, an extra **pressure drop of approximately 15 kPa** was added to the sum of the pressure losses from the main circuit, the maximum branch circuit, and the radiators. Since the individual circuits are arranged in **parallel**, the overall pressure drop is determined by the **maximum value among the parallel branches**. The final total pressure drop, incorporating all contributing elements, is summarized in the **table below**.

Table 8: Pressure drop values of Radiator System

Max pressure drop among circuits (2)	Δp (Pa)	1325.8
Pressure drop of one radiator	Δp (Pa)	150
Main pipe pressure drop	Δp (Pa)	300
Additional valves (thermostatic, angle), fittings	Δp (Pa)	15000
Total Pressure drop	Δp (Pa)	16775.8

To integrate the calculated pressure drop into the IESVE model for accurate pump sizing, the following procedure was applied. Using the total system pressure drop and the formula shown below, the effective pump power and the pump absorbed power were computed, assuming a total pump efficiency (η_{tot}) of 0.6. Subsequently, the specific pump power (SPP) was determined using the corresponding equation, representing the final parameter to be entered into IESVE. This ensures that the modeled pump accurately reflects the real operating conditions of the hydronic distribution system.

$$P_W = V_W * \Delta p_{tot} \text{ [W]} \quad (8)$$

$$P_t = P_w/\eta_{tot} \text{ [W]} \quad (9)$$

$$P_{spec} = P_t/V_w \text{ [W/(l/s)]} \quad (10)$$

Table 9: Radiator System's Pump technical data

Total Pressure drop	Δp_{tot} (Pa)	16775.8	Calculated
Water Volumetric flow rate	V_w (m^3/s)	0.000069	Calculated
Pump Effective Power	P_w (W)	1.165	Calculated
Pump Absorbed Power	P_t (W)	1.942	Calculated
Pump Specific Power	P_{spec} (W/(l/s))	27.96	Calculated

2.1.5.3. Configuration 2 – Radiant Floor System

Figure 11 illustrates the preliminary design of the radiant floor layout for the case study apartment. For modeling simplicity in IESVE, the thermal output of all loops was assumed to be equal. This approach facilitated hydraulic balancing and ensured stable simulation behavior. The piping network is arranged in a **parallel circuit configuration** branching from the central manifold, as shown in Figure 11.

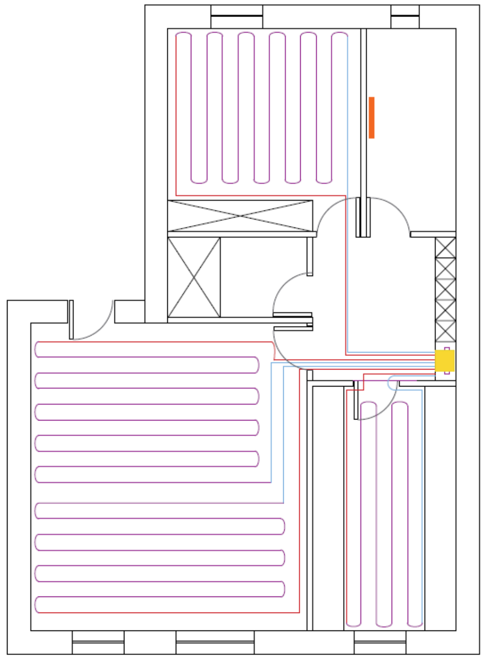

Figure 11: Radiant Floor System layout

The sizing process began with the **total heated floor area** and the previously determined **maximum sensible heating demand**. Using these values, the **reference heat output** was calculated for each heating zone. To simplify the calculations, the system was divided into **four loops**, serving the main zones of the apartment.

By knowing the $\mathbf{Q_{need}}$ value and assuming a **water supply temperature of 30 °C**, a **30 cm spacing between pipes** was selected for system implementation. This spacing was determined using the **reference chart from the manufacturer's datasheet**, which provides the recommended pipe layout and performance parameters for radiant floor installations under the specified operating conditions.[39]

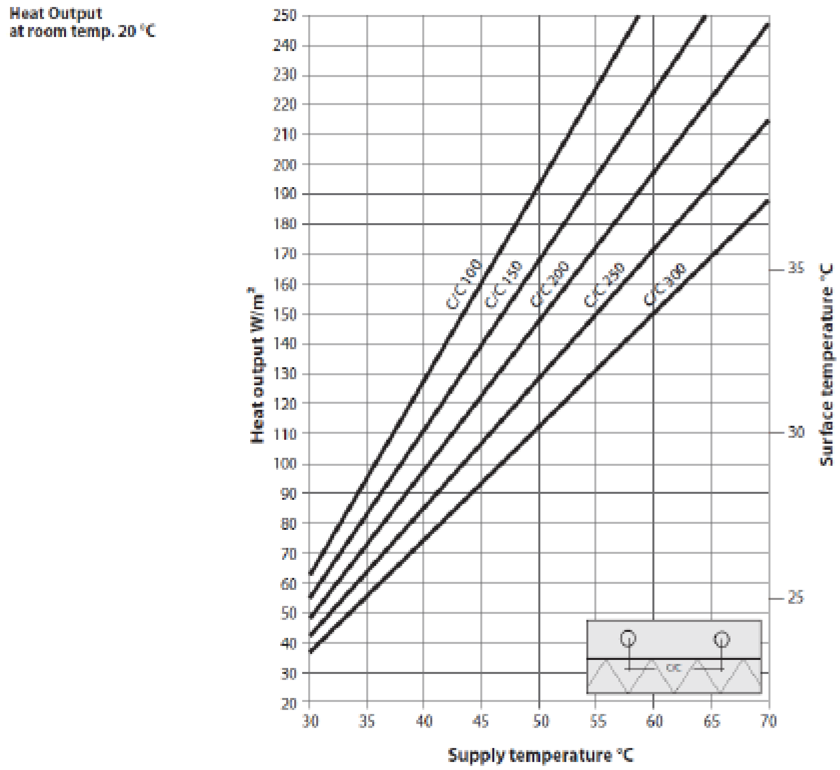

Figure 12: Radiant floor pipes space based on heat output and supply temperature from technical datasheet

The **reference temperature difference (ΔT_{ref})** was then calculated using the mean water temperature—derived from the supply and return temperatures—and the ambient design temperature. Considering a **return temperature of 25 °C** and an **ambient temperature of 20 °C**, the resulting mean water temperature is **27.5 °C**, yielding a **ΔT_{ref} = 7.5 °C**.

Using this temperature difference and the corresponding equations, the **reference heat output** and **loop lengths** were calculated based on the assumed number of loops derived from the layout design.

$$Q_{out,ref} = Q_{need} * A_{pan} = Q_{need} * (A/N_{loop}) \quad (11)$$

$$l_{loop} = A_{pan} / cc \quad (12)$$

The final results, including the thermal and geometric parameters of each loop, are summarized in **Table 10**.

Table 10: Radiant Floor system calculated technical data

Sensible heating energy need for an hour	Qsens	2.5	kW
Area	A	83	m^2
Needed heat output per floor area	Qneed	30.12	W/m^2
Supply Temperature	Tsup	30	˚C
Distance between pipes	cc	0.3	m
Supply & Return water temperature difference	ΔTw	5	˚C
Reference temperature	Tref	7.5	˚C
Number of loops	Nloop	4	-
Reference Heat output	Qout,ref	500	W/loop
Length of Loop	Lloop	55.33	m/loop

The radiant floor piping system employs **Danfoss FH PE-Xa EVOH five-layer pipes (16×2 mm)** [39], a model specifically designed for radiant floor applications. Based on the design calculations and using formula below, each circuit carries a **mass flow rate of 0.02 kg/s**, leading to the selection of this pipe type.

$$Q = m_w * c_{p,water} * \Delta T_w \qquad (13)$$

Although the manufacturer allows a maximum circuit length of 400 m, the calculated design required only **55 m per loop**, corresponding to a **water capacity of 6.255 L per circuit**. The total weight of the embedded piping system was computed considering the multiple layers of material used in the floor buildup, including insulation, screed, and finishing layers.

$$W_{pan}=W_{pan} * A_{pan} = w_{pan} * (A/N_{loop}) \qquad (14)$$

Table 11: Radiant Floor each loop weight calculations

	Thickness	Density	specific weight	Pan weight
	m	kg/m^3	kg/m^2	kg/loop
Ceramic Tiles	0.015	2300	34.5	
Adaptive layer for Radiant Floor	0.05	1800	90	
Total			124.5	2066.7

Regarding the distribution system, only the **main supply pipe** connecting the boiler to the manifold was considered for **thermal loss/gain calculations**. Since the radiant floor circuits are entirely embedded within the conditioned zones, any heat exchange from these pipes contributes directly to space heating and is therefore not treated as a distribution loss.

For the main pipe, proper sizing was carried out by first determining the **total volumetric flow rate**, obtained as the sum of the flow rates from all radiant floor loops, which equals **0.12 L/s**. Based on this value, and according to the manufacturer's data, the appropriate pipe type and size were selected as **20×2 mm**. Because any thermal transmittance from this pipe to the internal environment would not significantly contribute to useful heating, an **insulation layer** was applied to minimize unwanted heat transfer.

The **placement of the boiler and manifold** follows the same configuration as in the radiator system, resulting in a **main pipe length of 1.2 meters** for both the supply and return lines. The insulation layer has a **thickness of 13 mm** and a **thermal conductivity of 0.027 W/m·K**. Using the same calculation method presented in Section 5.1.2 for the radiator configuration, the **thermal transmittance** was determined to be **0.12 W/m·K**. Considering an **average water temperature of 27.5 °C**, an **ambient temperature of 20 °C**, and the **radiant floor system operating time of approximately 1,097 hours per year**, the resulting **annual heat loss** through this main pipe is estimated at **1.23 kWh/year**.

This corresponds to a **distribution loss of approximately 0.05%**, a negligible value that nonetheless has been included in the simulation for completeness. As discussed previously for the radiator configuration, this minimal loss is due to the installation of both the **distribution pipes and boiler within the conditioned thermal zone**, where any heat dissipation ultimately contributes to the overall heating demand of the apartment.

Finally, the **pump head pressure** was calculated using the same approach as in the radiator configuration, taking into account the pressure drop along the main pipe, the manifold, valves, and the maximum pressure drop across the longest circuit. These hydraulic parameters were subsequently implemented in IESVE's ApacheHVAC module to simulate the thermal performance and operating efficiency of the radiant floor system.

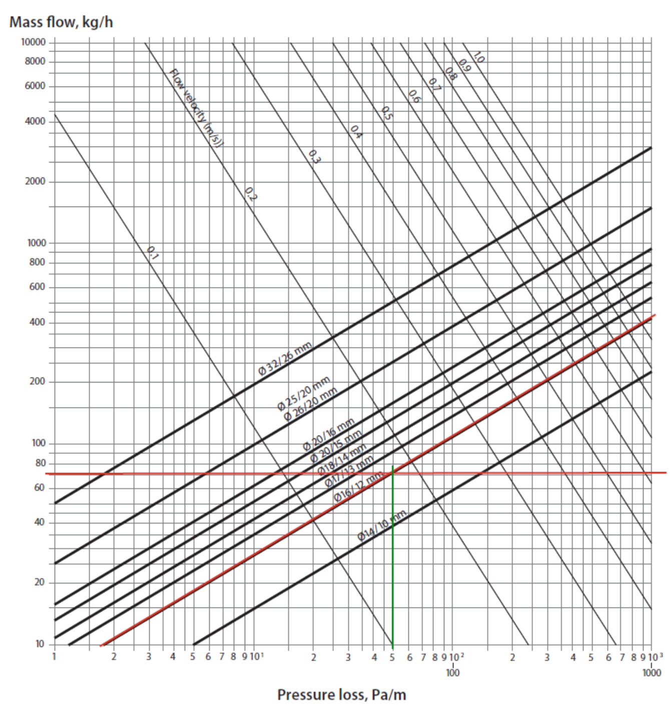

Figure 13: pressure drop as a function of mass flow rate and pipe diameter from technical datasheet

The chart shown above is provided by the pipe manufacturer and is used to determine the **pressure drop** as a function of **mass flow rate** and **pipe diameter**. This chart was applied to estimate the pressure loss in each radiant floor loop. As established in the previous calculations, the **mass flow rate for each loop** is **72 kg/h**; using this value in the manufacturer's chart for the selected pipe size yields a **pressure drop of approximately 50 Pa/m**. By multiplying this value by the **length of each circuit**, the total **pressure drop per loop** was obtained, as summarized in the **table below**.

Table 12: Radiant Floor's pump technical data

main pipe pressure drop	Δp	396	Pa
each loop pressure drop	Δp	2766.67	Pa
additional pressure drop (manifold, valves, fiting, joints)	Δp	15000	Pa
Total pressure drop	Δp	18162.67	Pa
Water Volumetric flow rate	V_w	0.00012	m^3/s
Pump Effective Power	P_f	2.17	W
Pump Absorbed Power	P_t	3.62	W
Pump Specific Power	P_{spec}	30.27	W/(l/s)

2.1.5.4. Configuration 3 – Fan Coil System

The third heating configuration consists of three fan coil units serving the main living areas. For this configuration, the fan coil operates with a supply temperature of 50 °C and a return temperature of 40 °C.

The fan coil units were selected based on the design load requirements for the apartment. The chosen model, **Carisma CRC13** [40], was used for all three units to simplify both hydraulic and thermal modeling. Manufacturer data provided the required inputs for water-side and air-side parameters, including nominal capacity, airflow rate, and fan power. Using these data, the mass and volumetric flow rates for each unit and for the total system were calculated. In addition, fan-side efficiency calculations were performed to evaluate the electrical energy consumption associated with air circulation.

Among the input data provided by the **fan coil manufacturer**, one parameter required for accurate modeling and simulation in **IESVE** is the **outlet air temperature** after passing through the fan coil unit. To determine this value, the **heat exchange equation** shown below was applied. Since the fan coil operates as a **heat exchanger**, and the analysis focuses on the **heating season**, the **latent heat component** was neglected, considering only the **sensible heat exchange** between the air and the hot water circuit. By applying this formula, the **temperature difference** between the inlet and outlet air was calculated to be **19 °C**, resulting in an **outlet air temperature of 39 °C**, as summarized in the **table below**.

$$Q = m_w * c_{p,water} * \Delta T_w \,,\ \ Q = m_{air} * \Delta h \qquad (15)$$

$$Qsens = m_{air} * c_p^{ma} * \Delta T \qquad (16)$$

Table 13: Fancoil units technical data

Fan coil model (CRC 13)			
Speed [Min]			
Water Temperature [50-40]			
Heat energy need	Q_{sens}	2.5	kW
model heat output	Ph / Qh	0.68	kW
water volumetric flow rate	V_{water}	58	l/h
air flow rate	V_{air}	105	m^3/h
water specific heat	cp_w	4.18	kJ/kg.K
air inlet temperature	$T_{in,air}=T_{set}$	20	˚C
air outlet temperature	$T_{out,air}$	39.0	˚C
Water pressure drop	Δp_w	0.3	kPa
Fan power	P_{fan}	16	W
air density	p_{air}	1.2	kg/m3
air mass flow rate	m_{air}	126	kg/h
air mass flow rate	m_{air}	0.035	kg/s
air specific heat	cpma	1.02	kJ/kg.K
Air temperature difference	ΔT	19.0	
fan pressure drop	ΔP_{fan}	250	pa
Total efficiency	η_{total}	45.57%	
motor & fan efficiency	$\eta_{fan}=\eta_{motor}$	67.51%	

To include the **fan efficiency** and **motor efficiency** parameters in the IESVE model, the formula shown below was applied. The calculation was performed under the assumption of a **fan pressure drop of 250 Pa**, using the corresponding **volumetric airflow rate** provided by the manufacturer. In this analysis, both the **fan efficiency** and **motor efficiency** were assumed to be equal, reflecting the combined performance of the air-handling components within the fan coil unit. The resulting calculated values are summarized in Table 13.

$$P_{fan} = (\Delta P_{fan} * V_{air}) / \eta_{total} \text{ [W]} \quad (17)$$

$$\eta_{total} = \eta_{fan} * \eta_{motor} \quad (18)$$

The hydraulic distribution system for this configuration follows a similar arrangement to the radiator system, incorporating a manifold that distributes hot water from the boiler to each fan coil unit. The main supply and return pipes between the boiler and manifold are composed of **Giacomini R999 20×2 mm** [37]pipes, while the secondary circuits connecting to the fan coils use **16×2 mm** pipes of the same type.

The same procedure used for the radiator configuration is applied to compute thermal transmittance and heat transfer along the pipes, using the formulation in Section 2.1.5.2. Table 14 compiles the resulting mass flow rates, pipe thermal transmittance, lengths, heat transfer rates, and pressure drops.

Table 14: Fancoil system pipe circuits thermal data

	mass flow rate	linear thermal transmittance	Length	heating energy gain to the thermal zone	pipes pressure drop
	mw (kg/s)	Ψ (W/m.K)	Length (m)	Qgain (kWh/Yr)	Δp (Pa)
main pipe (boiler to manifold)	0.064	0.198	1.2	6.86	300
circuit 1 (manifold to fan coil)	0.016	0.184	18.94	100.51	1325.8
circuit 2 (manifold to fan coil)	0.016	0.184	16.98	90.11	1188.6
circuit 3 (manifold to fan coil)	0.016	0.184	11.2	59.44	784

Calculations assume an average water temperature of 45 °C, an ambient air temperature of 20 °C, and the selected pipe types/sizes insulated with 13 mm on the main distribution and 10 mm on the branch circuits, with insulation thermal conductivity λ = 0.04 W/ m.K. Based on preliminary simulations, the fan-coil operating time is 1,143 h. Figure 14 illustrates the placement of the fan coils and the towel dryer within the apartment.

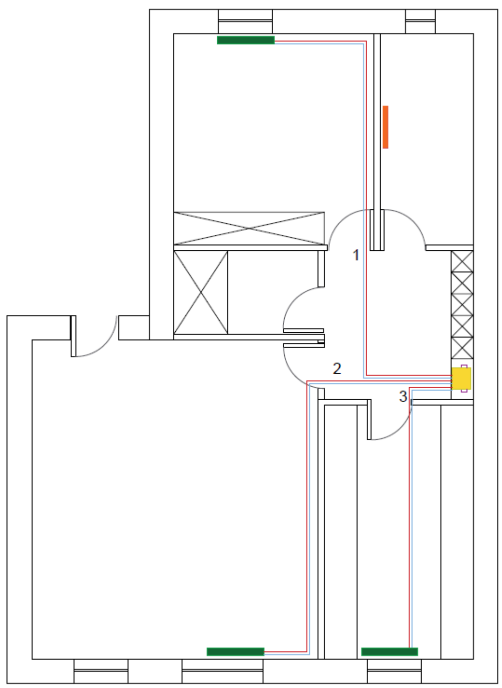

Figure 14: Fancoil system layout

The total pressure drop for each circuit was determined from manufacturer charts, and the pump head was computed as the sum of the primary circuit losses, manifold losses, valve resistance, and the maximum pressure drop among the parallel branches.

Table 15: Fancoil system pressure drop calculations

Max pressure drop among circuits (1)	Δp (Pa)	1325.8
Pressure drop of one Fan coil	Δp (Pa)	300
Main pipe pressure drop	Δp (Pa)	300
Additional valves (thermostatic, angle), fittings	Δp (Pa)	15000
Total Pressure drop	Δp (Pa)	16925.8

The values presented below are implemented in IESVE to model the appropriate pump, following the calculation methodology described in Section 2.1.5.2.

Table 16: Fancoil system's pump technical data

Total Pressure drop	Δp_{tot} (Pa)	16925.8
Water Volumetric flow rate	V_w (m^3/s)	0.000016
Pump Effective Power	P_w (W)	0.27
Pump Absorbed Power	P_t (W)	0.45
Pump Specific Power	P_{spec} (W/(l/s))	28.21

Thermal gains or losses through the pipework were also estimated using the same methodology applied in the radiator configuration. However, since all distribution pipes are located within the heated zones, these thermal exchanges are considered beneficial to the overall space heating. The calculated results are summarized in Table 14, which presents the selected component types, associated heat transfer to the thermal zone, and circuit pressure losses used to determine the final pump sizing. To ensure high precision in the system configuration, the distribution losses within the model are set to **0.31%**, representing the heat loss occurring along the main pipe between the boiler and the manifold.

2.1.5.5. Towel dryer Assumptions

In the energy modelling phase, the **radiant floor** and **fan coil systems** were sized and simulated considering only their primary emission components, namely the radiant floor pipes in the radiant floor configuration and the fan coil units in the fan coil configuration. This simplification was adopted for modelling purposes.

However, due to spatial constraints in the bathroom and the need to provide both partial space heating and towel drying functionality services that are inherently covered by radiators in the radiator system an **electric towel dryer** was included in the radiant floor and fan coil configurations to ensure functional equivalence among the systems. The technical specifications of the selected towel dryer are provided in the corresponding section.

It should be noted that the initial energy modelling phase accounted solely for the main emission systems, namely the fan coils and radiant floor components. The additional energy consumption and environmental impact associated with the towel dryer are subsequently incorporated and analyzed in the Life Cycle Assessment section for each respective system.

An electric towel warmer model "COMFORT 500x900" (170 W, IP44), equipped with the R3 thermostat, has been selected as a compact and energy-efficient solution for bathroom integration. This unit, produced by the Ukrainian manufacturer Laris Perfect, features a dry heating element and is designed for wall-mounting in small interiors such as bathrooms, entryways, or dressing areas. The R3 electronic thermostat offers intuitive control via a single multifunction button and includes a three-level heat regulation (min–mid–max), with maximum surface temperature reaching 55 °C. For operational efficiency, the system integrates a 3-hour timer and a default ECO mode that automatically reduces the heating level after 24 hours of continuous use, enabling up to 70% electrical energy savings. The device also supports rapid heating mode, memory function, and overheat protection. With a modern, powder-coated matte finish and minimal footprint, this 170 W unit provides localized drying and comfort without burdening the primary climate control system, making it an optimal choice for bathrooms with existing fan coil heating systems.[41]

2.1.5.6. Boiler Performance Modeling

The Immergas Victrix Tera VIP V2 condensing boiler's performance was modeled in IESVE using the "Equation of the Curves" method.[42]This method represents efficiency as a polynomial function of boiler part-load ratio and water temperature. In our implementation, we adopted the bi-quadratic polynomial form. The boiler's rated (baseline) point was defined at return water 60 °C and full load (PLF=1.0), where the manufacturer's data correspond to an efficiency of ~0.87 (87% HHV). The boiler's minimum useful heat output is 2.7 kW, closely matching the building heating demand, so the model needed to accurately capture efficiency down to low loads.

Rendimento termico utile al 100% Pn (80 / 60 °C)	%	97,5
Rendimento termico utile al 30% del carico nom. (con temperatura di ritorno 30 °C)	%	109,5
Rendimento termico utile al 100% Pn (40 / 30 °C)	%	107,7
Rendimento termico utile al 30% del carico nom. (40 / 30 °C)	%	106,6

Figure 15: part of boiler technical data sheet related to PLF and temperatures

$$f\text{Ept}\,(p,T) = (C00 + C10*p + C20*P^2 + C01*T + C02*T^2 + C11*p*T)/\,C_{norm} \qquad (19)$$

$$p=PLF\ ,\ T=T_{cbin}\ ,\ \ C_{norm}\ \ \text{t.c}\ \ f\text{Ept}\,(1,T)=1 \qquad (20)$$

Assumption: variation with T and p are independent.

Efficiency Data Processing

Efficiency curves were generated from the manufacturer's technical datasheet ("Victrix Tera VIP V2") by processing the tabulated LHV-based efficiencies for various load and temperature conditions. The datasheet reports, for example, 107.7% LHV efficiency at full load with 40/30 °C return. These high values exceed 100% because they use the lower heating value (LHV) basis. We converted all LHV efficiencies to the higher heating value (HHV) basis by dividing by 1.11. This yields the actual combustion efficiencies (≤100%) used in the model.

$$\eta\_HHV = \eta\_LHV/1.11 \qquad (21)$$

The converted HHV efficiencies were then tabulated in two separate interpolation grids (each covering the range of interest in part-load fraction and return temperature, respectively). Specifically:

- The first table was constructed by interpolating HHV efficiency as a **function of Partial Load (PLF)** at fixed return temperatures (30/40).

Table 17: Boiler's efficiency as function of PLF

PLF (30/40)	η
0	0
0.1	0.99
0.2	0.99
0.3	0.99
0.4	0.98
0.5	0.98
0.6	0.98
0.7	0.98
0.8	0.97
0.9	0.97
1	0.97

- The second table **T_ret** was interpolated for HHV efficiency as a function of return water temperature at fixed load fractions (PLF=1).

Table 18:Boiler's efficiency as function of Temperature

T-ret (PLF=1)	η
0	1
10	0.99
20	0.98
30	0.97
40	0.94
50	0.91
60	0.88
70	0.85
80	0.82
90	0.79
100	0.76

- These two tables were multiplied element-wise to produce a combined efficiency matrix f(PLF)·(T_ret), representing efficiency as a function of both PLF and return temperature.

Table 19: Boiler's efficiency as function of PLF & Temperature

T-in/ PLf	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.00	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.97	0.97	0.97
10	0.00	0.98	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.96	0.96
20	0.00	0.97	0.97	0.97	0.96	0.96	0.96	0.96	0.96	0.95	0.95
30	0.00	0.96	0.96	0.96	0.95	0.95	0.95	0.95	0.95	0.94	0.94
40	0.00	0.93	0.93	0.93	0.92	0.92	0.92	0.92	0.92	0.91	0.91
50	0.00	0.90	0.90	0.90	0.89	0.89	0.89	0.89	0.89	0.88	0.88
60	0.00	0.87	0.87	0.87	0.86	0.86	0.86	0.86	0.86	0.85	0.85
70	0.00	0.84	0.84	0.84	0.83	0.83	0.83	0.83	0.83	0.82	0.82
80	0.00	0.81	0.81	0.81	0.80	0.80	0.80	0.80	0.80	0.79	0.79
90	0.00	0.78	0.78	0.78	0.77	0.77	0.77	0.77	0.77	0.76	0.76
100	0.00	0.75	0.75	0.75	0.74	0.74	0.74	0.74	0.74	0.74	0.73

Baseline Normalization and Curve Form

The full-load, 60 °C-return point was used as the normalization reference. Following IESVE practice, the efficiency curve was normalized so that the factor fEpt (p,T_{CBin}) equals 1 at the rated condition. In effect, the absolute HHV efficiency at (PLF=1, 60 °C) was set to 0.85, and all other efficiency values were divided by this rated efficiency. This yielded a normalized efficiency multiplier for each PLF and temperature.

$$\eta / \eta\_rated = f\mathrm{Ept}\ (p, T_{CBin}) \qquad (22)$$

Table 20:Boiler's efficiency as function of PLF & Temperature after Normalization

T-in/ PLf	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	1.16	1.16	1.16	1.15	1.15	1.15	1.15	1.14	1.14	1.14
10	1.15	1.15	1.15	1.14	1.14	1.14	1.14	1.13	1.13	1.13
20	1.14	1.14	1.13	1.13	1.13	1.13	1.12	1.12	1.12	1.12
30	1.13	1.13	1.12	1.12	1.12	1.12	1.11	1.11	1.11	1.10
40	1.09	1.09	1.09	1.09	1.08	1.08	1.08	1.07	1.07	1.07
50	1.06	1.05	1.05	1.05	1.05	1.04	1.04	1.04	1.04	1.03
60	1.02	1.02	1.02	1.01	1.01	1.01	1.01	1.00	1.00	1

The polynomial curve coefficients were then fitted to this normalized data.

Coefficient Extraction

Coefficients were determined in stages by isolating part-load and temperature effects:

- **PLF-only fit at 0 °C:** Using the row of data at return = 0 °C, we fitted a quadratic polynomial in PLF to the normalized efficiencies. This yielded the coefficients C20, C10, and C00. A regression (e.g. linear fit) to the 0 °C curve produced these values (visualized in a plot of normalized efficiency vs. PLF).

C20= 0.000000000000007 , C10= -0.0272 , C00= 1.1656

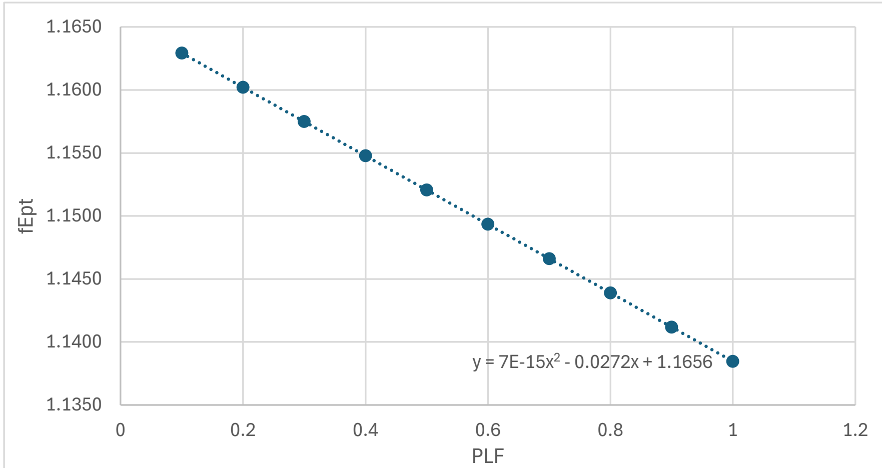

Figure 16: Normalized efficiency vs. PLF at 0 degree

- **Temperature effects:** Next, for each non-zero return temperature, we subtracted the 0 °C baseline efficiency to isolate the temperature-dependent component. The differences f(PLF, T_{CBin}) – f(PLF,0) averaged over PLF for each T_{CBin}. This provided mean efficiency gains at each return temperature, which were then used to fit the temperature coefficients (C02,C01) by plotting these averaged differences versus T_{CBin}(a secondary regression). In practice, this yielded the remaining polynomial coefficients for the bi-quadratic curve.

C02= -0.00004 , C01= 0.00004

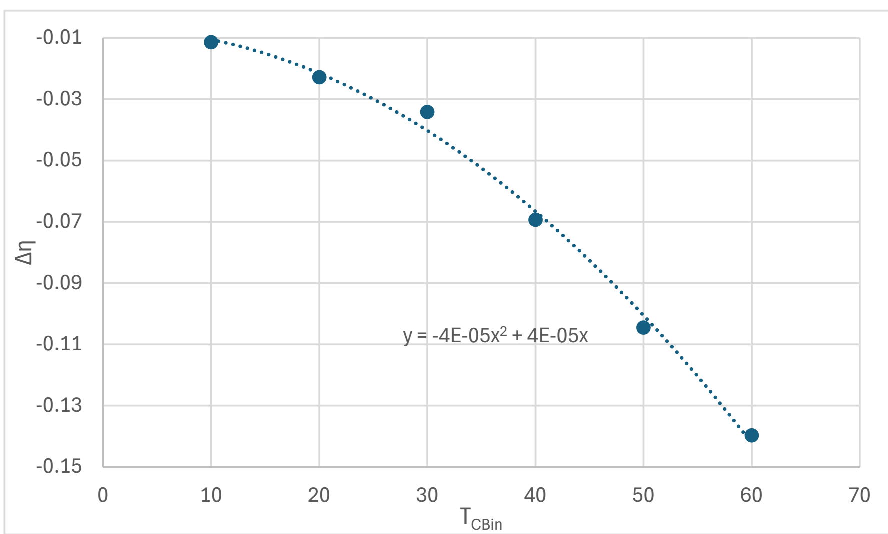

Figure 17: Averaged efficiency vs. T_{CBin}

Model Validation

The resulting performance curve was validated against the original datasheet points. For example, we compared the model's predicted HHV efficiency at 30% load (PLF=0.3) and at full load (PLF=1.0) for a return temperature of 30 °C against the datasheet's LHV efficiencies (107.7%) converted to HHV. The model's predictions matched the datasheet values to within 0.03% in absolute efficiency. This exceptionally small deviation confirms that the polynomial curve accurately reproduces the manufacturer's performance data at key operating points.

$$f\ Ept\ (p,T) = (1.1656 + -0.0272*p + 0 * p^2 + 0.00004 * T + -0.00004 * T^2) / C_{norm} \qquad (23)$$

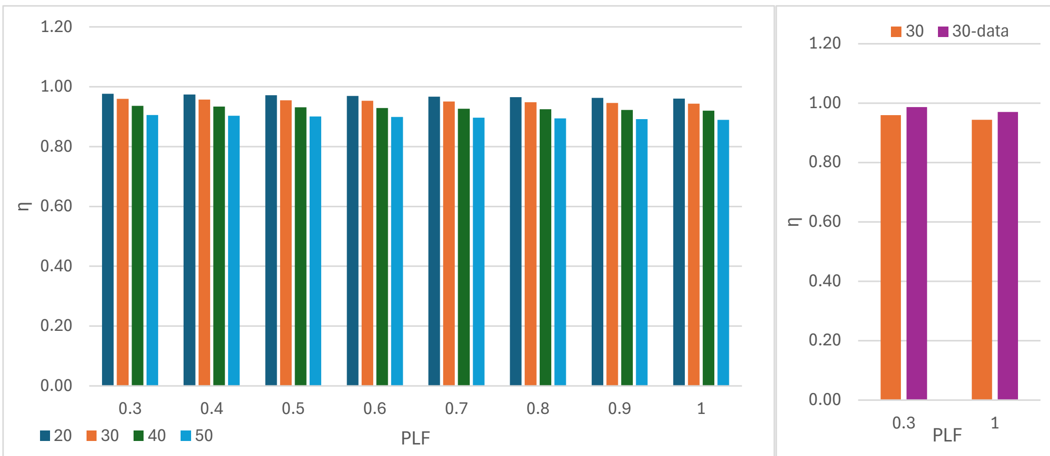

Figure 18: Boiler Efficiency at different PLF and Temperatures with comparison between calculated and technical data at 30 degree

2.1.6. Final Results (Hourly Simulations with ApacheHVAC)

In the following section, the results of the energy modelling of the three systems and the subsequent simulations will be presented. The focus will be on the energy consumption of different parts of the systems and their efficiencies. In addition, the results will examine the behaviour of the three systems on specific days, such as the coldest and mildest days, to assess the performance of the systems at different locations and the comfort level of the case study in terms of temperature.

2.1.6.1. Energy

The graphs below present the **monthly results of total energy** associated with the generation, distribution, and emission subsystems, together with the **heating energy need of the thermal zone**. Each graph corresponds to one of the three heating configurations and shows how the system behaves in every month of the year. A quick visual inspection immediately confirms that, due to the climatic conditions of Milan, the months of **January, February, and December** exhibit the highest heating demand in all configurations, while the period from late spring to early autumn shows negligible load. It is important to clarify the meaning of the energy groups shown in the figures: **Generation Input** represents the energy absorbed by the boiler from primary energy, here natural gas, to produce hot water; **Generation Output** is the energy delivered to the hydronic distribution system after passing through the boiler; and **Emission Energy** corresponds to the heat actually delivered by the terminal units (radiators, radiant floor panels, or fan-coils). The **differences between these energy groups** represent the cumulative inefficiencies or losses occurring in each subsystem—boiler conversion, piping distribution, and emission performance—providing insight into how effectively each configuration transforms primary energy into useful heating for the building.

- Radiators;

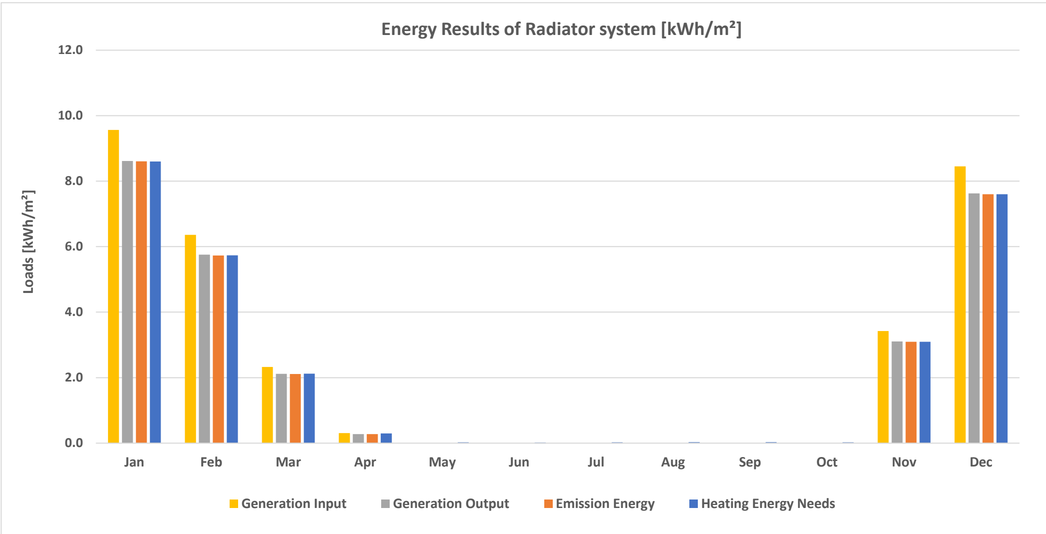

Figure 19: Energy results of Radiator System

- Radiant Floor

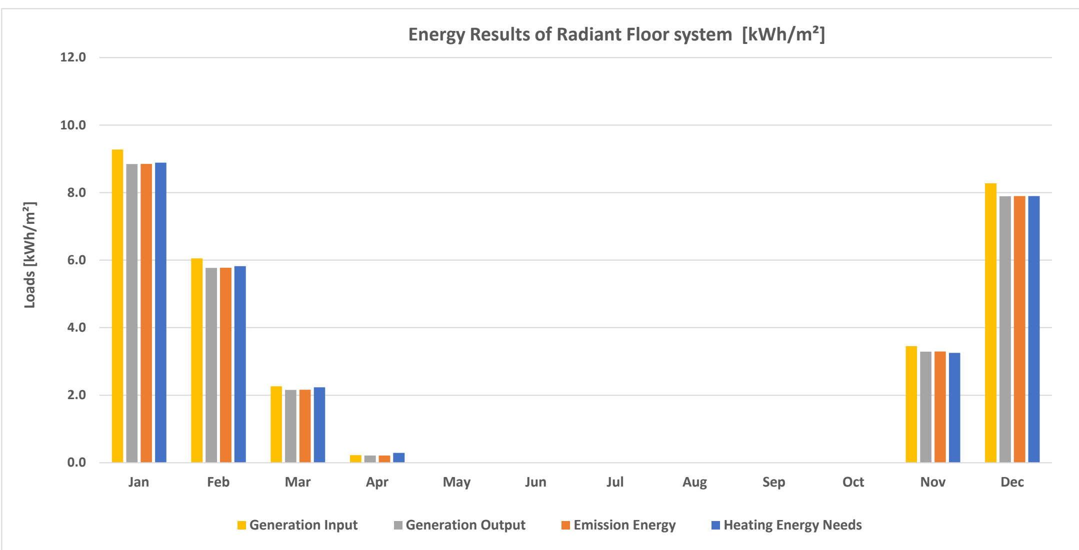

Figure 20:Energy results of Radiant Floor System

- Fancoils

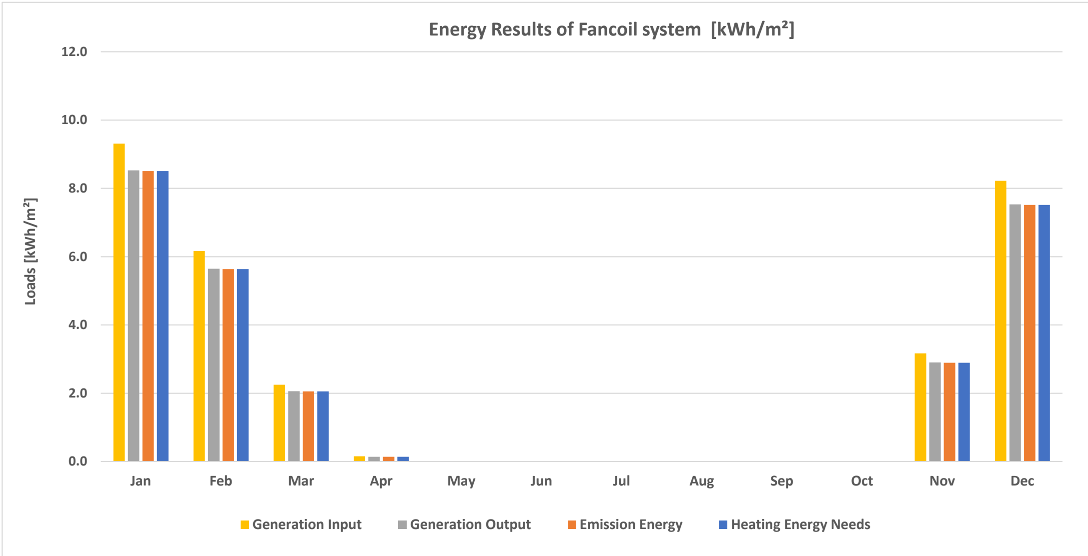

Figure 21:Energy results of Fancoil System

Table 21: Final energy results of all systems

Total \ System Type	Radiator	Radiant Floor	Fancoil
Operation Hours [h]	920	1097	1143
Generation Input [kWh]	2526.54	2452.83	2429.56
Generation output [kWh]	2282.41	2338.18	2225.59
Emission Energy [kWh]	2275.63	2340.00	2220.32

A comparison of the monthly energy profiles and annual results for the three heating systems shows that, although the **heating energy needs** are practically identical in all configurations and follow the same seasonal pattern (with peaks in January, February and December and almost no demand from April to October), the way each system supplies and emits this energy is different. The **radiator system** records an annual **generation input of 30.44 kWh/m²**, which is reduced to **27.50 kWh/m² of generation output** and **27.42 kWh/m² of emission energy**, indicating a clear but moderate gap between the energy taken from the boiler and the heat actually emitted in the zones; this system works for **920 hours/year**, i.e. with shorter but more intense operating periods. The **radiant floor system** shows the smallest separation between the energy groups, with **29.55 kWh/m² of generation input**, **28.17 kWh/m² of generation output** and **28.19 kWh/m² of emission energy**: here the input value is slightly lower than for radiators, while output and emission are closer to each other and to the heating needs curve throughout the winter months, confirming that almost all generated heat is effectively delivered through the floor; the system operates for **1,097 hours/year**, reflecting longer but lower-power operation. Finally, the **fan-coil system** presents the highest annual **generation input after radiators (29.27 kWh/m²)** but the lowest **generation output (26.81 kWh/m²) and emission energy (26.75 kWh/m²)**, so the gap between input and emission is the widest among the three, which is also visible in the winter graphs as a more pronounced vertical distance between the curves; this system has the **longest operating time (1,143 hours/year)**, consistent with a convective emitter that runs more continuously. Overall, the joint reading of the monthly graphs, annual energy values and operating hours shows that the radiant floor system achieves the closest match between generation, emission and heating needs over the year, radiators perform with slightly higher input for a shorter number of hours, and fan-coils require a comparable input energy but emit less heat to the zones while operating for the longest time.

During the analysis of the energy modelling results, a potential question may arise regarding the slight differences observed in the **heating energy demand** among the three systems, particularly when comparing the months of **November and December**. The reason for these differences lies in the **dynamic energy balance** calculated within the simulation software, which accurately represents the performance characteristics of each system.

Although several input parameters—such as occupancy, solar gains, equipment gains, and ventilation rates—are identical across the scenarios, the heating systems themselves operate differently. As a result, the **indoor temperature distribution** varies slightly between configurations. These variations affect the **surface temperatures within the building**, which in turn influence the **mean radiant temperature** and ultimately alter both internal and external **conduction losses**.

Radiators deliver a combination of **radiant and convective heat**, radiant floor systems provide a **higher radiant fraction** and warm a larger surface area, and fan coils operate primarily through **convective heat transfer**. Consequently, each system produces different surface temperature distributions. Since conduction losses are dependent on the temperature difference between interior and exterior surfaces, higher surface temperatures can lead to increased heat transfer through the envelope. This effect is particularly evident in the radiant floor system, where slightly higher heating demand values are observed compared to the other systems.

It is therefore appropriate to evaluate each system based on its **own calculated heating demand**, rather than comparing all configurations to a preliminary estimation of building heating demand. The graph below illustrates the variation in **mean radiant temperature** across the three systems, showing higher values for the radiant floor system and lower values for the fan coil system. These differences contribute to variations in conduction losses among the systems.

It should be noted, however, that the variation in heating demand between the systems remains relatively small, in the range of approximately **1–2 kWh/m²·year**.

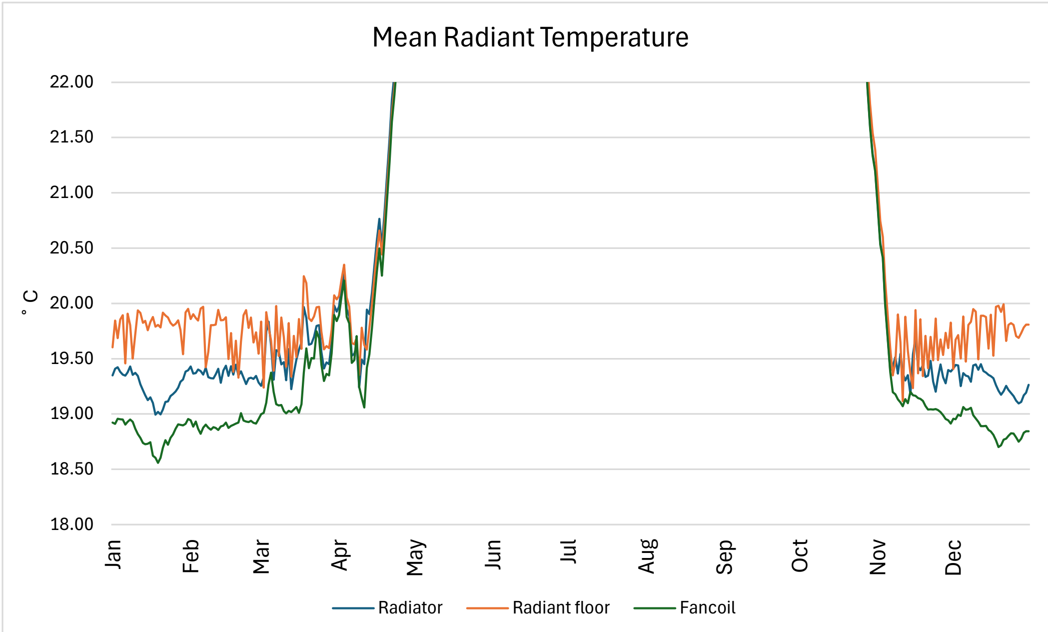

Figure 22: Yearly Mean radiant temperature of all systems

2.1.6.2. Dynamic Behaviour of Heating Systems During Representative Winter and Mid-Season Days

The next section presents the hourly performance analysis of the three heating configurations using four representative days from the annual simulation. For each system, two winter days (15 and 16 January) and two mid-season days (9 and 10 April) are examined. January represents one of the coldest periods of the year, with the highest heating demand, while April is selected as a milder, low-load period that still requires intermittent heating. The graphs include the following parameters: indoor air temperature of the thermal zone, outdoor air temperature, unit water supply temperature entering the terminal unit, and unit water return temperature leaving it, together with the upper (21°C) and lower (19°C) heating setpoint limits. By analysing these representative days, it becomes possible to evaluate how each system responds to variations in outdoor temperature, how well it maintains the indoor temperature within the comfort band, and how the water temperature behaviour of each terminal unit (radiators, radiant floor, or fan-coils) reflects its operational strategy and thermal inertia. This comparison highlights the differences in dynamic performance, response speed, and stability of indoor conditions among the configurations.

- Radiators

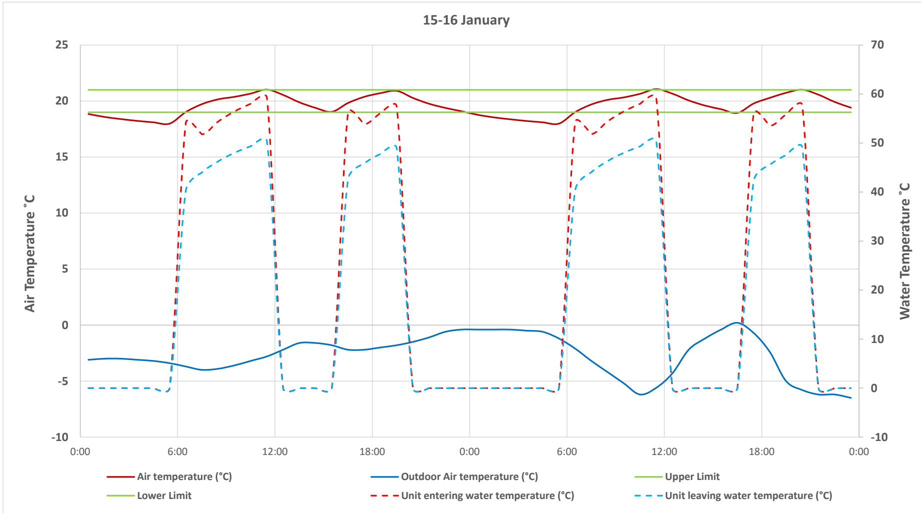

Figure 23: Thermal zone and inlet/outlet water temperatures of radiators in 15-16 of January

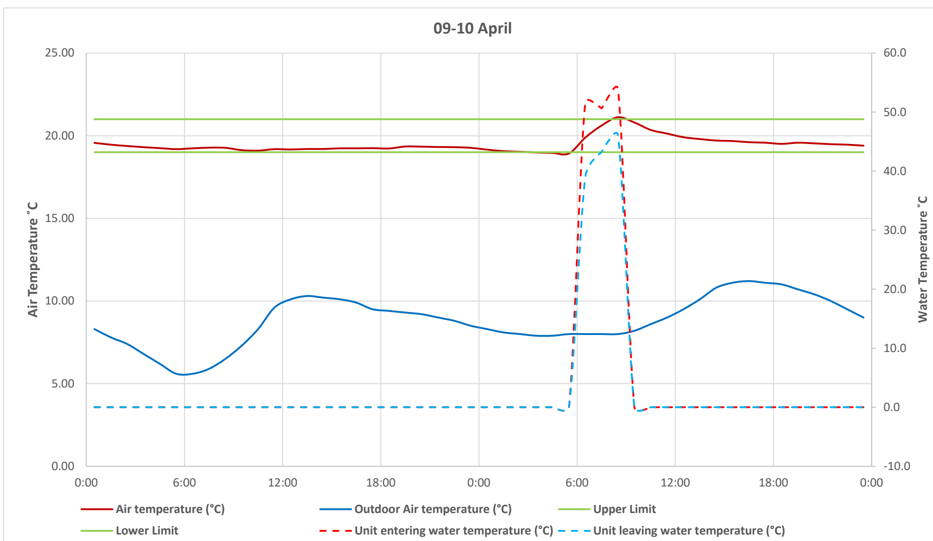

Figure 24:Thermal zone and inlet/outlet water temperatures of radiators in 9-10 of April

On 15–16 January, radiators activate sharply once the heating schedule begins and outdoor temperatures remain below freezing. Water supply temperature rises rapidly to **55–60°C**, producing short but intense heating cycles. Indoor air temperature stays within the comfort band, but small oscillations occur due to the **low thermal mass** and **on/off operation** of radiators. During the night, indoor temperature gradually declines but remains within acceptable limits.

In April, heating is required only for a brief morning period. A short spike in water temperature restores indoor conditions, after which the system remains off for the rest of the day. Indoor temperature stays nearly constant between **19.0–20.0°C**, showing that radiators respond quickly but only when triggered, and otherwise rely on the building's thermal inertia.

- Radiant Floor

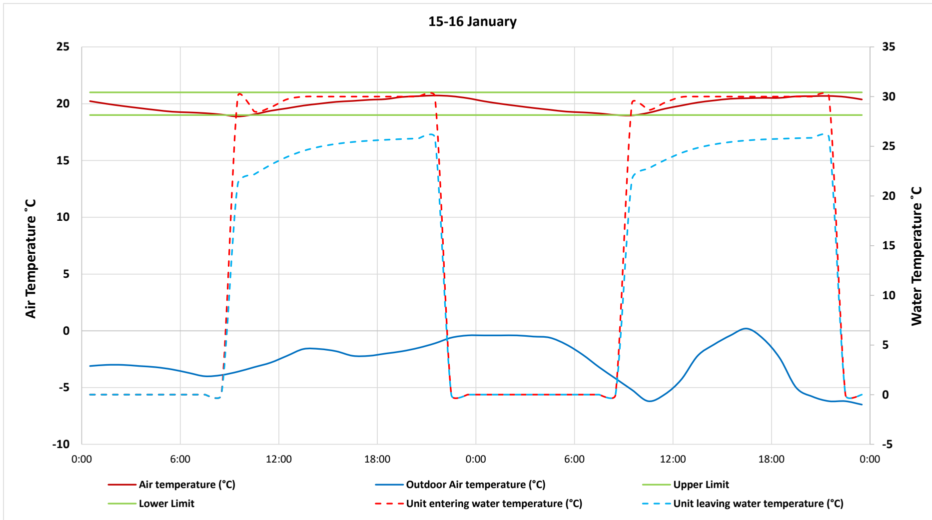

Figure 25: Thermal zone and inlet/outlet water temperatures of radiant floor pipes in 15-16 of January

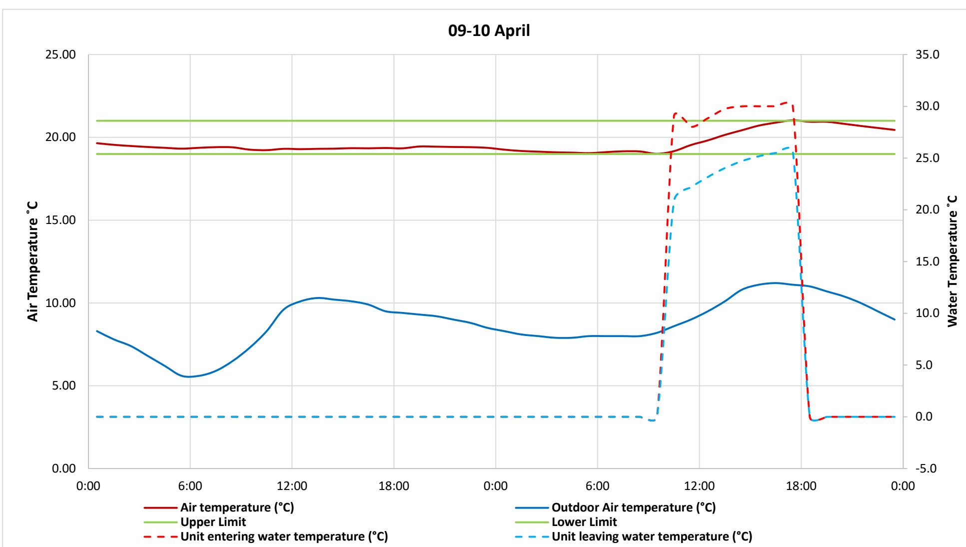

Figure 26: Thermal zone and inlet/outlet water temperatures of radiant floor pipes in 9-10 of April

The radiant floor shows a distinctly smoother behaviour. In January, water supply temperature stabilizes around **28–30°C**, and cycles are long and gradual. Indoor air temperature is extremely stable (variations typically below **±0.2°C**), as the slab's thermal mass continues to release heat even during the night when the system is off.

In April, only a brief activation occurs early in the morning, with water temperature increasing modestly before returning to baseline. Indoor temperature remains effectively flat throughout the day. The radiant floor's strong inertia allows the system to maintain comfort with minimal cycling and without noticeable temperature drops outside operating hours.

- Fancoils

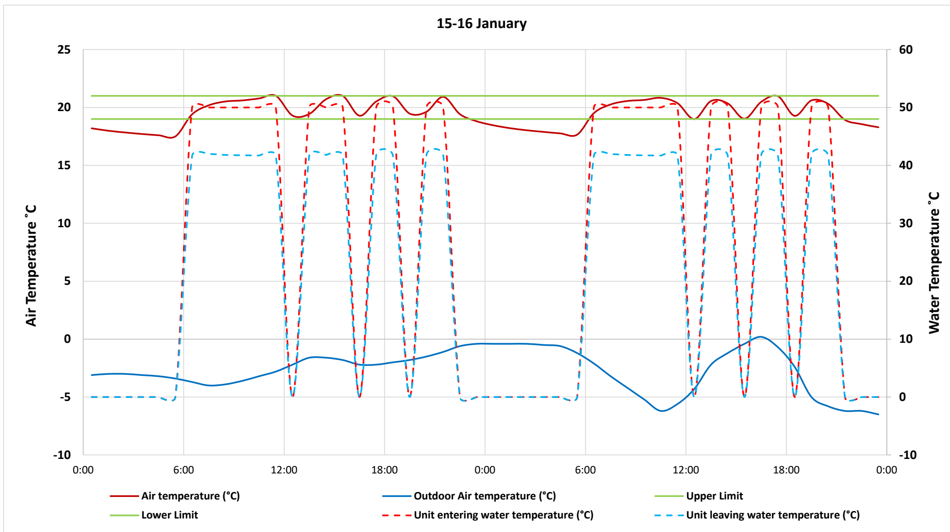

Figure 27:Thermal zone and inlet/outlet water temperatures of fancoils in 15-16 of January

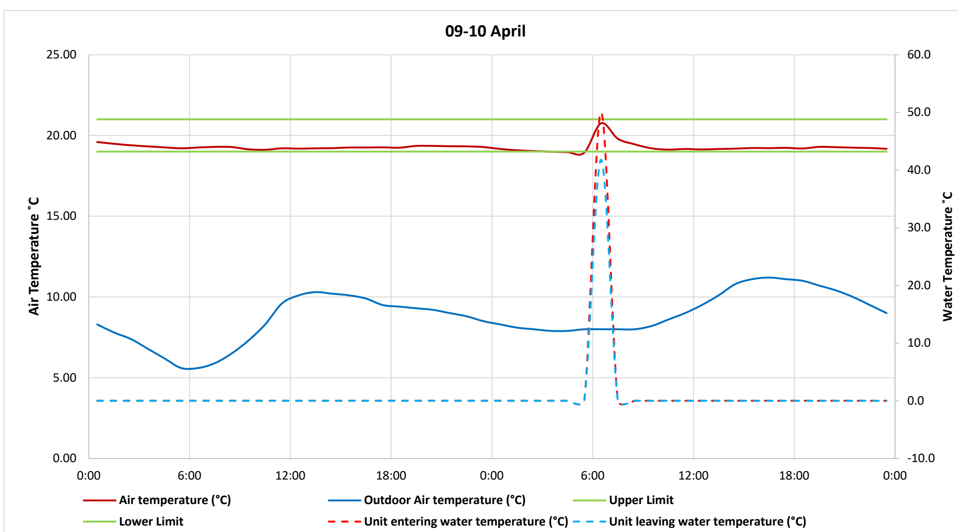

Figure 28:Figure 26: Thermal zone and inlet/outlet water temperatures of Fancoils in 9-10 of April

Fan-coils display the **highest cycling frequency**. In January, the system produces repeated, short heating bursts with supply temperatures around **45–50°C**, matching the heating schedule window. Indoor temperature stays within comfort limits but shows more noticeable fluctuations than the radiant floor and a slightly more oscillatory pattern than radiators.

In April, the system activates only once during the early morning. Because fan-coils have almost no thermal storage, indoor temperature stability relies entirely on the thermostat and short-duration convective heating pulses. Once outdoor conditions become mild, the fan-coil remains off and indoor temperatures remain stable but without the smoothing effect seen in the radiant floor system.

Across both winter and mid-season conditions, the radiant floor system provides the **most stable indoor air temperature**, with almost no oscillations and smooth water-temperature behaviour. Radiators show moderate fluctuations and higher supply temperatures but heat zones effectively within the schedule window. Fan-coils respond rapidly but cycle the most frequently, producing more pronounced short-term variations.
Because heating is restricted to **daytime only**, all systems show a natural decline in indoor air temperature during night hours, yet radiant floors compensate best through stored heat in the slab, radiators retain moderate stability, and fan-coils rely purely on daytime convective bursts. These differences clearly illustrate how thermal inertia and emitter type govern the **dynamic heating performance** of each configuration.

2.1.6.3. Indoor Air Temperature Distribution Over the Year

To evaluate the thermal comfort performance of the three heating configurations, the annual distribution of **indoor air temperature** was analysed using four temperature categories: **below 18°C**, **18–19°C**, **19–21°C**, and **above 21°C**. For each system, a graph shows the **percentage of total yearly hours** during which the indoor air temperature falls within each category. These distributions provide a clear overview of how effectively each configuration maintains comfort throughout the year, independently of monthly energy consumption or operational hours. This analysis is particularly important because maintaining indoor temperatures close to the comfort band (typically **19–21°C** for heating seasons) indicates not only efficient energy use but also the system's capacity to respond to both outdoor climatic variations and internal loads. By comparing the three systems, we can understand how the characteristics of each emitter—radiators, radiant floor panels, and fan-coils—translate into different indoor temperature stability patterns across the year. The results also help highlight situations where a system tends to underheat (temperatures <18°C), remains close to the lower edge of comfort (18–19°C), stays within the ideal comfort band (19–21°C), or overheats (>21°C). Taken together, these graphs provide valuable insight into **thermal comfort quality**, **system control behaviour**, and **overall indoor environmental performance**.

- Radiators

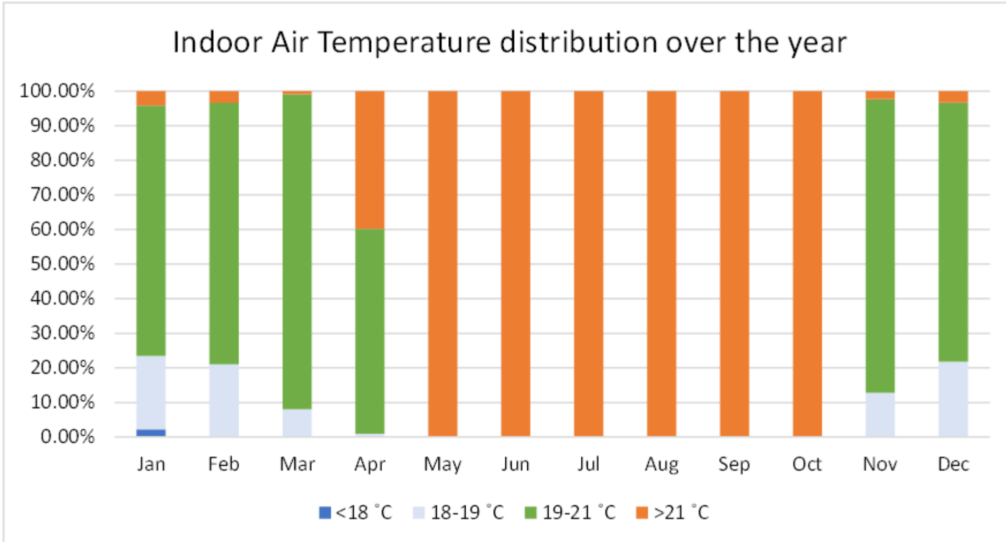

Figure 29: Yearly Indoor air temperature distribution with Radiator system

- Radiant Floor

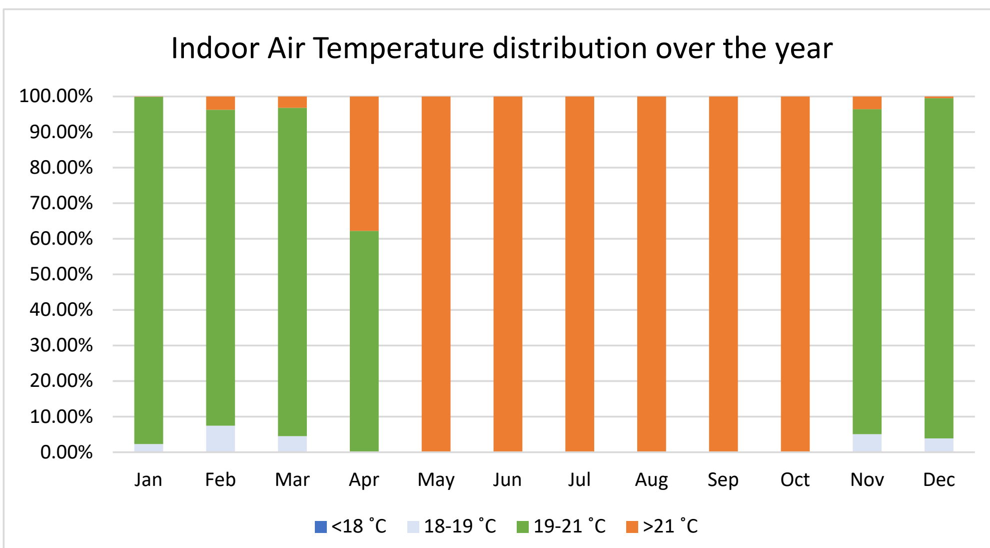

Figure 30: Yearly Indoor air temperature distribution with Radiant Floor system

- Fancoils

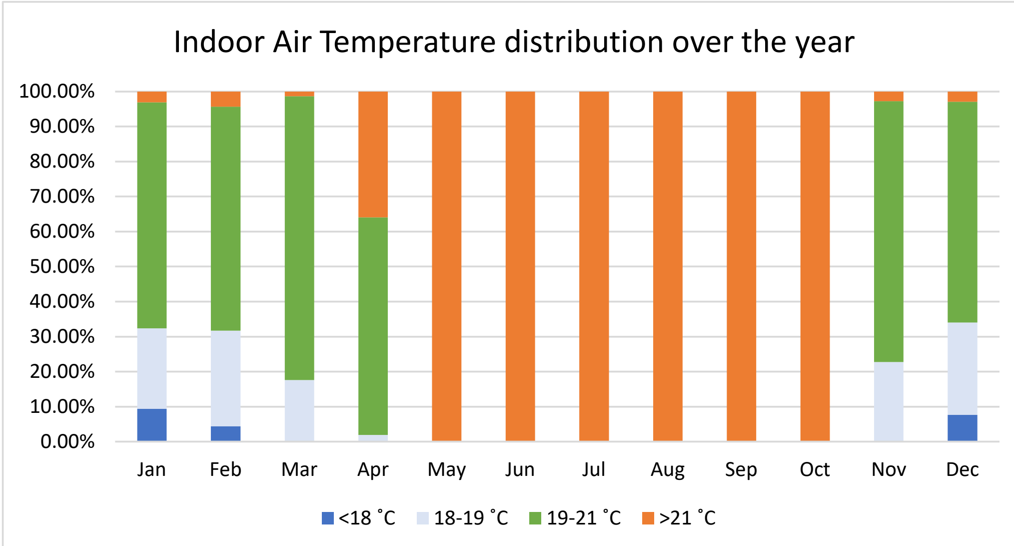

Figure 31: Yearly Indoor air temperature distribution with Fancoil system

The annual indoor air temperature distribution highlights significant differences in thermal comfort performance among the three heating configurations. The **radiator system** maintains indoor temperatures predominantly within the **19–21°C comfort band**, but shows noticeable portions of hours in the **18–19°C** category during winter months, and a very small share **below 18°C**, mainly due to the limited thermal inertia of radiators and the heating schedule (active only from 06:30 to 22:30), which allows the indoor temperature to drop slightly during night-time setback. The **radiant floor system** performs best overall: almost all winter hours fall within **19–21°C**, with only negligible time in the 18–19°C band and virtually no hours below 18°C, demonstrating the stabilizing effect of the slab's thermal mass, which continues to release heat even when the system is off. In contrast, the **fan-coil system** exhibits the widest spread across categories, with a greater share of hours in **18–19°C** and some hours **below 18°C** in January and February, reflecting its very low thermal inertia and rapid cooling once heating cycles stop; occasional hours **above 21°C** appear in shoulder months due to the fast convective response of fan-coils leading to short-term overheating. Overall, the radiant floor system provides the most consistent comfort conditions, radiators offer acceptable performance with modest under-temperature periods, and fan-coils deliver adequate daytime comfort but show the greatest variability due to their intermittent and convection-dominated heating behaviour.

2.1.6.4. Boiler efficiency

In the previous sections, the condensing boiler was sized and modelled in IESVE based on identical design conditions for all three heating configurations. Although the same boiler model, capacity, and control setup are used across the radiator, radiant floor, and fan-coil systems, the **operating efficiency of the boiler varies** significantly among them. This difference arises not from the boiler itself but from the **water temperature levels required by each emitter type**, which strongly influence condensation effectiveness and seasonal efficiency. In the radiator configuration, the system typically operates with higher supply and return temperatures (approximately **50–60°C**), reducing the boiler's ability to condense and therefore lowering efficiency. The radiant floor configuration, by contrast, operates at much lower temperatures (**25–30°C**), allowing the boiler to remain in condensing mode for a greater portion of the heating season and thus achieving higher efficiency. The fan-coil configuration operates at intermediate temperatures (**50–40°C**), leading to efficiency values between the other two systems. The following section presents the boiler efficiency results for each configuration and provides a detailed comparison of their seasonal performance based on simulated operating conditions.

- Radiators

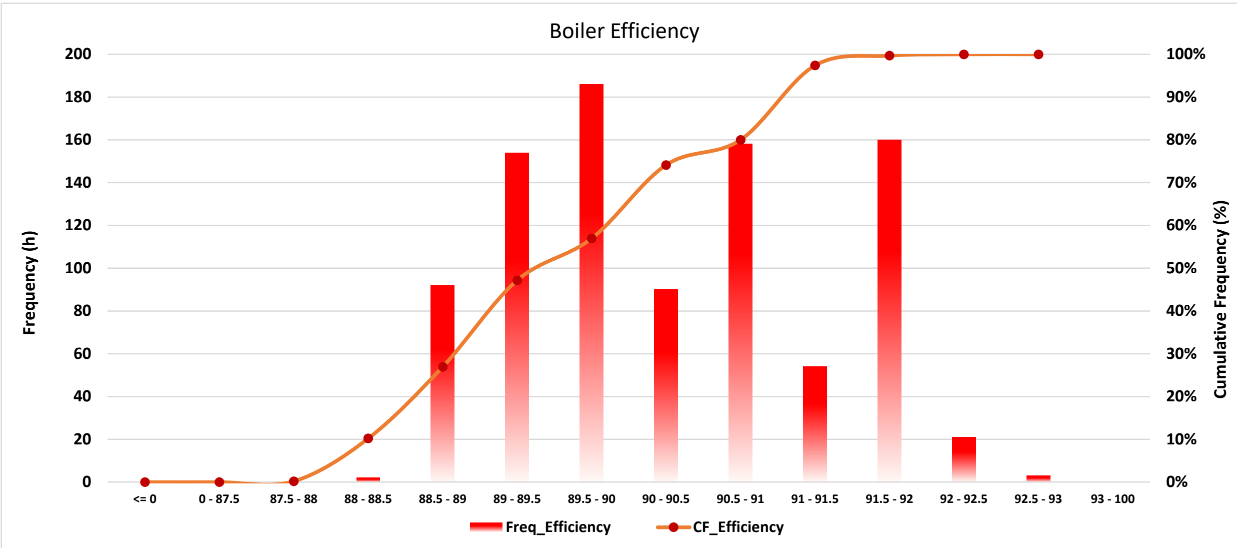

Figure 32: Boiler Efficiency within Radiator system

- Radiant Floor

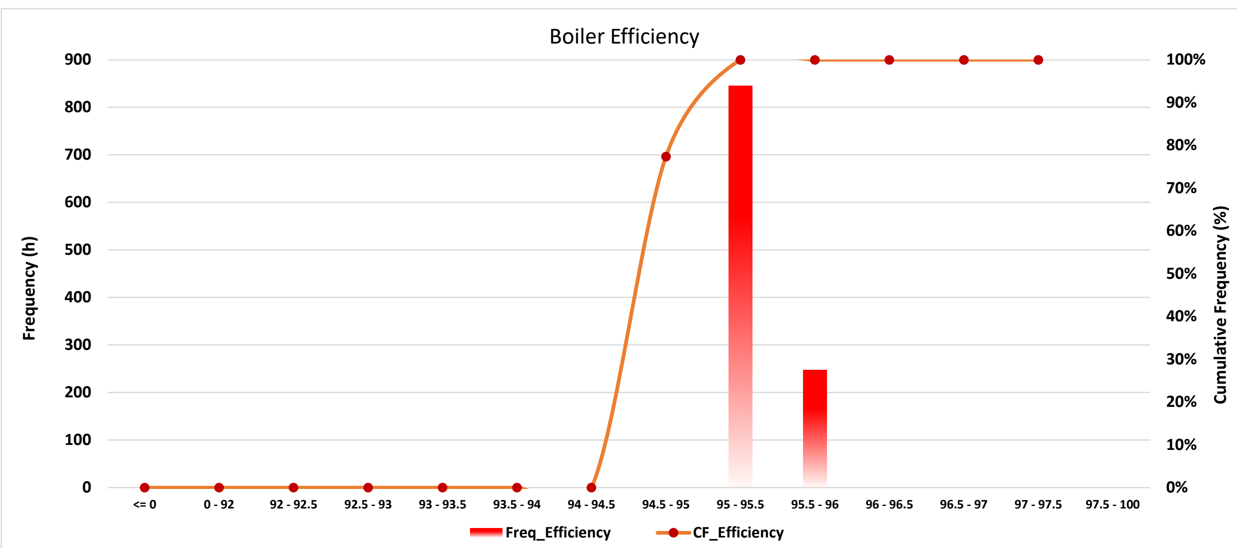

Figure 33: Boiler Efficiency within Radiant floor system

- Fancoils

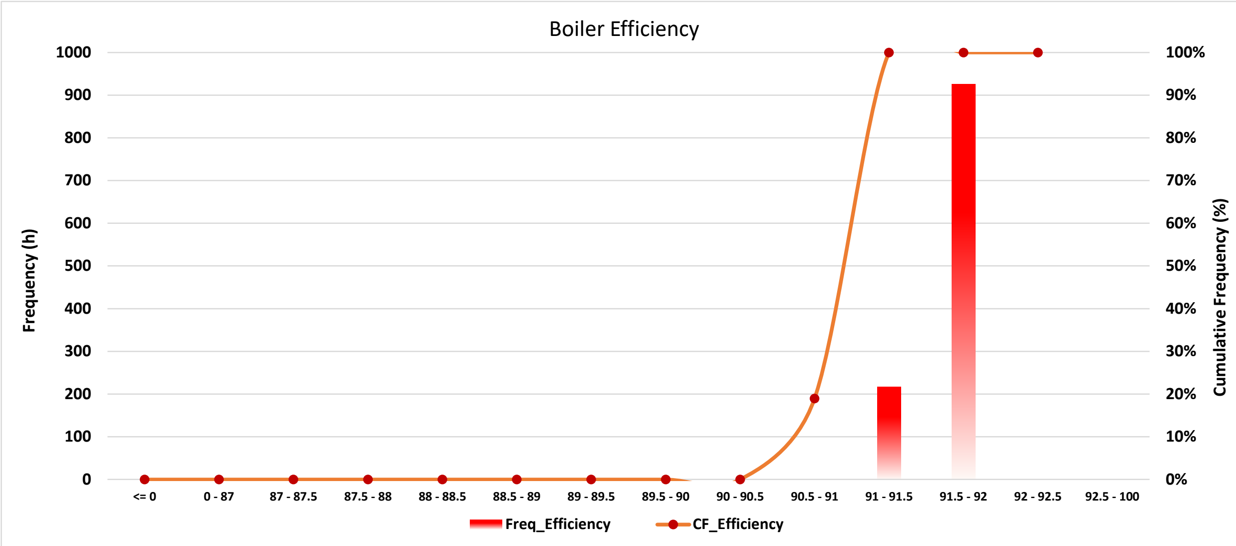

Figure 34: Boiler Efficiency within Fancoil system

Even though all three configurations use the **same condensing boiler model and sizing**, the efficiency results differ significantly because each heating system operates at **different water temperature levels**, which directly influence the boiler's ability to condense. The radiator system, with supply temperatures typically between **50–60°C**, exhibits a wider spread of efficiency values, with most operating hours falling between **88–92%**, and a noticeable tail extending down to 87–89%. The cumulative frequency curve rises gradually, indicating many hours spent in mid-efficiency ranges where return water temperatures are too high for full condensation. By contrast, the **radiant floor system** shows the highest overall efficiency: nearly all operating hours concentrate between **95–96%**, with the cumulative frequency curve reaching 100% very quickly. This narrow peak reflects the low supply/return temperatures of **25–30°C**, which keep the boiler in fully condensing mode throughout almost the entire heating season. The **fan-coil system** performs between the other two configurations, with the majority of hours in the **91–92%** range and a smaller block in the 90–91.5% bin. Its efficiency distribution is narrower than that of radiators but shifted to lower values than radiant floors, consistent with fan-coil operating temperatures of **50–40°C**, which allow partial condensation but still maintain relatively high return temperatures. Overall, the graphs show a clear hierarchy: **radiant floor achieves the highest and most stable boiler efficiency**, fan-coils provide intermediate performance, and radiators yield the lowest and most variable efficiency. This pattern directly reflects the thermodynamic behaviour of a condensing boiler, whose performance improves when **return water temperature decreases**, making low-temperature emitters significantly more favourable for seasonal efficiency.

2.1.6.5. Energy and power consumption

The final part of the results examines the **energy and power consumption** associated with the three heating configurations, focusing on the combination of fuel consumption for heat generation and the electrical power required to operate system components. In all configurations, the **condensing boiler** supplies the thermal energy for heating through **natural gas consumption**, while additional **electrical power** is required for the boiler's parasitic loads and the circulation pumps that drive hot water through the distribution system. The radiator and radiant floor systems therefore share the same types of electrical consumption—

parasitic power and pump power—reflecting their hydronic nature. The fan-coil configuration, however, requires an **additional electrical component**, as each fan-coil unit incorporates a **supply fan** that contributes to both power demand and overall system operation. The graphs in this section present the distribution of energy use and electrical power consumption for each configuration, enabling a comparison of how system type influences both natural gas demand and auxiliary electricity requirements. Once these graphs are introduced, a detailed comparison will highlight the relative impacts of emitter technology, water temperature, system cycling, and mechanical components on overall energy performance.

- Radiators

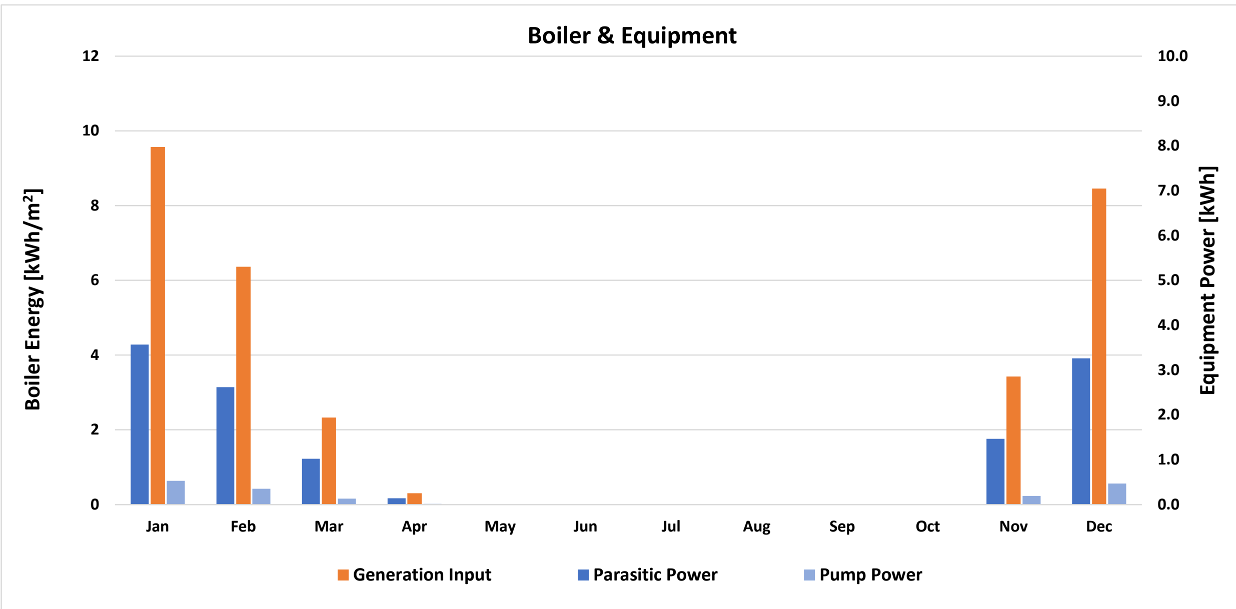

Figure 35: Energy and power consumption in Radiator system

- Radiant Floor

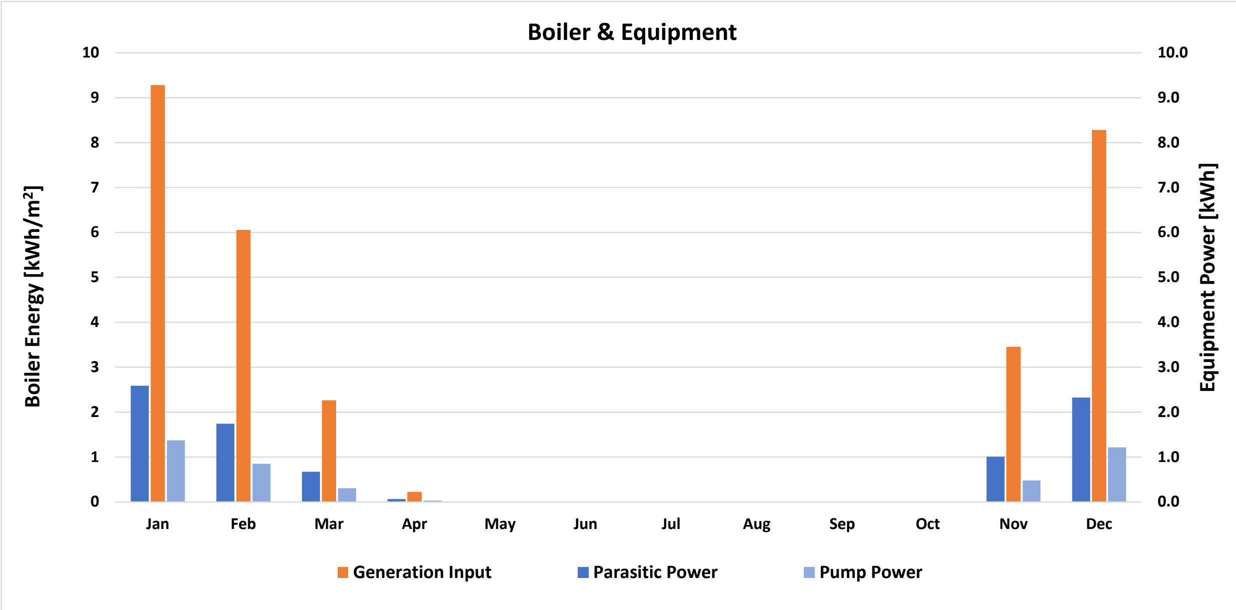

Figure 36: Energy and power consumption in Radiant floor system

- Fancoils

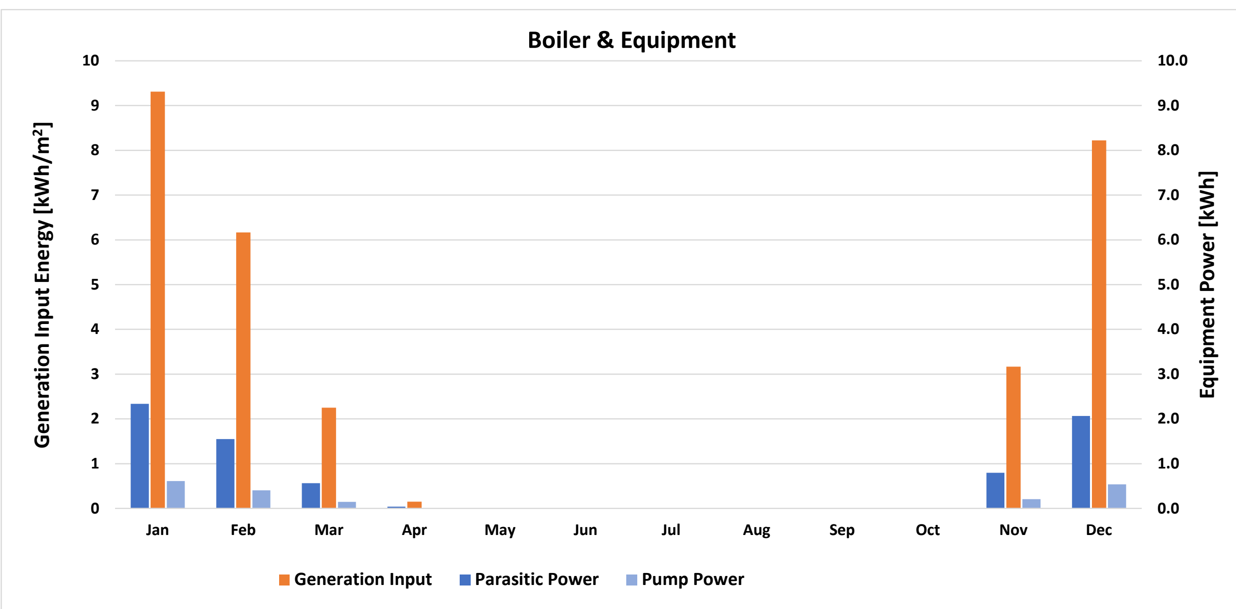

Figure 37: Energy and power consumption in Fancoil system

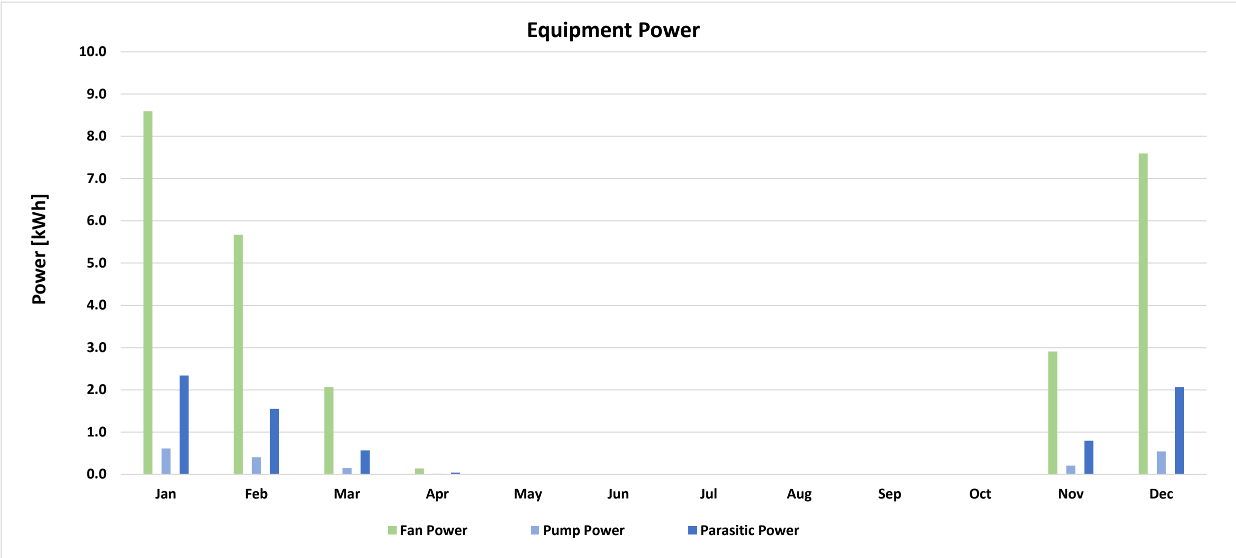

Figure 38: power consumption in Fancoil system

The monthly energy and equipment power profiles highlight how each heating configuration combines natural gas consumption with electrical auxiliary loads, reflecting the interaction between emitter characteristics, system cycling, and hydraulic operation. Across all systems, **generation input** follows the same seasonal trend, peaking in **January, February, and December**, with negligible heating demand during late spring and summer. However, the magnitude and distribution of **parasitic and pump power** differ among the three configurations, and the fan-coil system includes an additional **fan power component** that significantly increases its total electrical demand.

For the **radiator system**, the generation input is highest in the coldest months, aligning with earlier heating energy results. Parasitic power remains relatively consistent through the heating season, and pump power appears in proportion to system runtime, with values of around **4.5 kWh in January** and progressively lower toward spring. The radiator configuration therefore shows a clear relationship between heating load and auxiliary electrical consumption, driven entirely by boiler and pump operation, with no additional fan loads.

The **radiant floor system** shows a similar seasonal pattern in gas consumption, but with slightly lower pump power during peak months compared to radiators. This reflects the **longer but smoother operating cycles** associated with low-temperature radiant emission, which reduces pump cycling intensity. Parasitic power is again linked to boiler operation, but because radiant floors support higher boiler efficiency and more stable operation, the electrical auxiliary loads remain moderate and more evenly distributed. As expected for a hydronic-only emitter, no fan power contribution is present.

The **fan-coil system** exhibits the most complex electrical profile. While its generation input curve closely matches that of the other systems, one additional electrical component— **fan power**—substantially increases its total equipment demand. The first graph shows that pump and parasitic power behave similarly to the radiant floor case, reflecting the shared boiler and hydronic distribution system. However, the second graph reveals a large **fan power contribution**, particularly in January, February, and December, where fan consumption reaches values significantly higher than pump loads (e.g., nearly **9 kWh in January**). This is directly linked to the rapid cycling and active air movement of fan-coil units, which rely on continuous fan operation during heating periods, especially under cold outdoor conditions.

Overall, the comparison shows that **radiators and radiant floors rely solely on boiler parasitic loads and pump power**, with radiant floors slightly reducing electrical demand due to smoother hydraulic operation. Fan-coils, despite having similar natural gas requirements, incur substantially higher **electrical power consumption** because of their integrated fans, making them the configuration with the highest total auxiliary energy use. These results underline how emitter technology not only influences thermal performance and boiler efficiency but also has a significant impact on the **electricity requirements of the heating system**, affecting both operational energy and system-level efficiency.

2.2. Life Cycle Assessment

The **Life Cycle Assessment (LCA) is a method defined by the international ISO 14040 and ISO 14044** for analyzing the environmental aspects and potential impacts of product systems. As from the description this is only a method for adapting the Life Cycle Approach, which provides potential impacts. The word **potential** has a very important role here because the impacts can not be measured or specified in detail. The reason behind is LCA models generally are simplified and in generic, due to data approximation, simplification of characterization methods and… this method is helpful for **identification of environmental improvements** if different life cycle stages of a product also may help in design of new products or comparing products.

It should be noted that **LCA is based on simplifying assumptions**. This means in three parts starting with **steady state** which means all parameters that are defined with a behaviour are not changing over time as an example when considering a product to have 20 years of estimated service life we don't consider any possible damage during that time which may cause other emission during life cycle. **Linearity** as another assumption which could be interpreted that there is a linear relationship between the elementary flows such as a considered weight of a material of a product and their potential environmental impacts, which may be not linear in the real world. Third and last assumption **potential impacts**, which as described above, the impacts are relative expressions associated with the life cycle inventory and there is a lack of information about specific conditions of exposed environment.

According to the **international organization for standardization (ISO)** standards and by the **society of environmental toxicology and chemistry (SETAC)** an **LCA** consists of **4 stages**; **1.Goal and Scope 2.Inventory analysis 3.Impact assessment, and 4.Interpretation of results.**

Goal and scope stage is a descriptive stage of LCA which determins the problem and defines intended application, audience, stakeholders, objectives and scoope of the work.

In the **inventory analysis**, all the available information is quantified for the study, which includes the **polluting emissions to air, water and soil as well as the raw materials**.

Impact assessment evaluates the environmental impacts of results from inventory analysis. This part holds an important role in LCA, which is related to **selection of impact categories**, and presenting the results in each category based on different parameters.

Interpretation is where the results obtained are interpreted and the **uncertainties are evaluated**.

In the following sections these four stages are described, specifically in context of the study related to stages of assessment of three heating system types. The description is started with Goal definition of study and continues with steps of Scope and end with Interpretation of results after the impact assessment.

2.2.1. Goal

The first step of LCA is **Goal and Scope**, which here, description about Goal of the study is provided. This first stage has a crucial role in the assessment as the rest of assessment is highly dependent in this key phase.

This study is related to **LCA analysis of three different heating systems** for a case study building, which are **Radiator system, Radiant floor system and Fancoil system**. The essential application of this study is to determine the global environmental impacts of heating systems. These heating systems consist of different product and components with a unique objective to provide heating to the thermal zone in the system. so basically more than environmental impacts of total systems, it is about **identifying the hot spots**, the important components of each system that carry the **greatest environmental burdens** and more in deep the materials or processes that create these impacts inside each component.

The reason to carry out this study lies in creating an **awareness regarding selection of systems, components or products, materials** for Heating purpose of buildings. This awareness is not only useful for design phase of buildings or even for renovations but also for **manufacturing processes** of products associated with heating systems of buildings. The manufacturing processes is where materials are selected and can be one of the main points of **resource use**. This also may contribute to further developments in production of new items.

These kind of analysis can be helpful for specific **decision makers such as designer, engineer or a company**, which may cause changes in production or demand. This kind of analysis can create a thinking way in asking questions such as what will happen if I choose this type of system or product?!. So that designers choose wisely the product for their heating system and manufacturer choose wisely the material to produce the product from this point of view.

The following study is mainly **aimed at a technical audience** able to interpret the adapted methodology. Moreover, the following study is a **comparative analysis** as it is comparing different system under some **identical conditions for a case study**.

2.2.2. Scope

Following the first stage of LCA, Goal and Scope, in this section the Scope is taken into account with the following parameters: **product system function, functional unit and reference flows, product system, system boundaries, life cycle impact assessment methodology and data availability and assumptions**.

2.2.2.1. Product function

Based on the definitions in the Goal part of the Goal and Scope, here the product function is used to define **primary** and in possible case **secondary functions across product or systems** in order to be able to compare them based on the common function. In general the system function in this study could be defined as **Heating and towel drying inside the case study apartment**. The three different systems that are designed for the case study share a common function among themselves as providing heating to the building. Also a consideration of towel drying in the bathroom is the other function for this study, which components based on this function is selected in the systems. This definition of function for the systems allow us to determine a basis for the next parts of the Scope in the following parts.

2.2.2.2. Functional Unit and reference flows

According to ISO 14044, the **functional unit is "quantified performance of a product system for use as a reference unit**." Considering this, a comparison among systems is meaningful only if they are all based on the same function characterized. In this study, **The functional unit is considered to be 1 kWh of energy delivered** to the case study apartment (**83 m^2**) for heating and towel drying purpose by the HVAC system and components during the **whole reference study period, which is equal to 50 years.**

For the defined functional unit, the **reference flows correspond to the quantities of materials, components, and energy required** to provide space heating and towel drying over the 50-year reference study period. These include **emission devices** (radiators, radiant panels, fan-coil units), **distribution pipes and manifolds, Boilers, towel dryers, and operational energy consumption** (natural gas and electricity). The quantities of each reference flow vary among scenarios and constitute the basis for the life cycle inventory.

2.2.2.3. Product system

The product systems is defined in **standard ISO 14040 (2006a) as follows, "A collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product**".

For this study, the product system comprises all unit processes necessary to deliver the defined functional unit. The system includes production of heating emission devices, distribution pipes and manifolds, boilers and towel dryers. To be more specific the **foreground system** of this product system would be different for each configuration of heating systems, as an example for radiator system will be radiators distribution pipes and manifold and boiler, while the **background system would be production stage of materials** such as steel, copper, aluminum, etc, electricity production, natural gas extraction and production for the mentioned components. The product system was modeled by **linking foreground processes** (specific to each heating configuration) **with background processes derived from the ecoinvent database**.

Within the description of product system, two important flows are described, which are elementary flows and intermediary flows, which are considered between environment, technosphere of product system and product system. the **intermediary flows** define as flows of products that are used in system and **occur inside the technosphere**, however **elementary flows** are flows **directly extracted from the environment** and **emissions** to air, water and soil.

In this study as an example in the radiator system, the intermediary flows are considered as materials such as steel, aluminum or energy such as natural gas or water treatment and products. All of these are products or services exchanged within the economy. With different quantity the same description could be used for other heating systems in the study.

While the elementary flows, taking the same example of radiators system, are considered all the extractions of resources from environment such as iron, copper and emissions released to environment from natural gas for example which are CO_2, CH_4.

The following figures present simplified flowcharts of the product systems analyzed in this study, illustrating the structure of the three heating configurations considered: radiator system, radiant floor system, and fan coil system. The left side of each diagram shows the intermediary flows entering the system, including material inputs (e.g., steel, copper, aluminum, polymers), energy carriers (natural gas, electricity), and components such as pipes, manifolds, boilers, and emission devices. The central block represents the functional unit, defined as the delivery of 1 kWh of thermal energy to the reference apartment. The right side of the diagrams illustrates the output flows, including waste treatment processes (landfill, recycling, incineration).

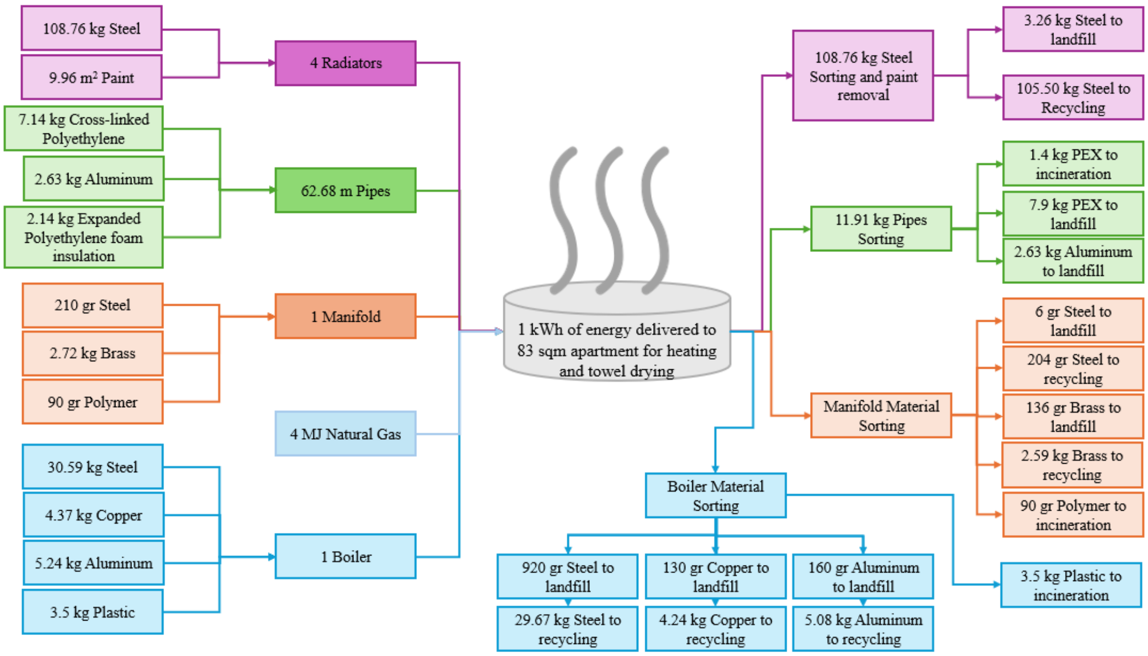

Figure 39: Radiator heating system – Product system flowchart

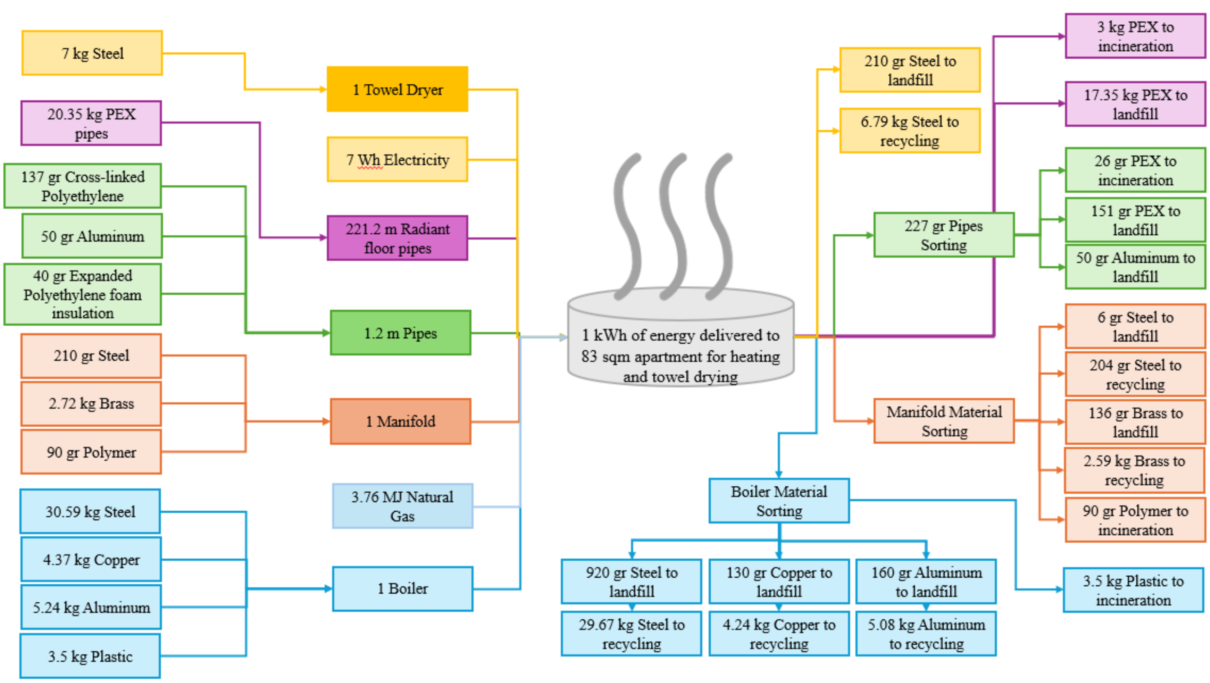

Figure 40: Radiant Floor heating system – Product system flowchart

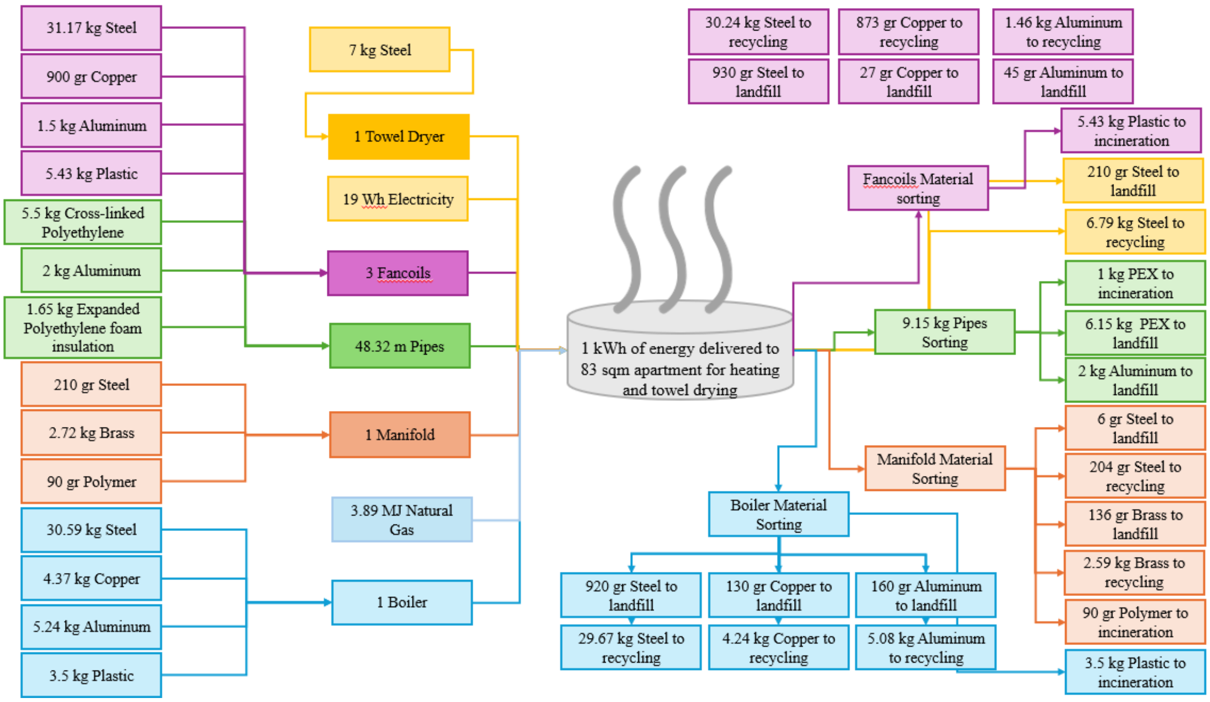

Figure 41: Fan coil heating system – Product system flowchart

2.2.2.4. System boundaries

System boundaries could be defined in three different categories of **technical, geographical and temporal**. These boundaries include all the necessary processes to assure the desired function in all scenarios. Further each category is described and defined for this study.

A. Technical system boundaries

The technical system boundaries of the present Life Cycle Assessment were defined in accordance with **ISO 14040/14044 and EN 15804 standards**. The product system includes all unit processes necessary to fulfil the primary function of the heating systems under analysis, namely radiators, radiant floor heating, and fan coil systems. The system boundaries were defined to ensure comparability among the three alternatives, meaning that all systems provide the same heating function within the apartment under identical operational conditions.

In accordance with EN 15804 modular structure, included modules are:

- **A1–A3: Production stage** (raw material supply, transport within manufacturing, manufacturing processes)
- **B4: Replacement of components** within the reference study period
- **B6: operational energy** for space heating generation
- **C3–C4: End-of-life treatment** (transport to waste treatment, waste processing, disposal)

- **Module D: Benefits and loads beyond the system boundary** (energy recovery from plastic incineration)

Excluded modules:

- A4–A5: Transport to construction site and installation processes, as the study focuses exclusively on the heating systems themselves and not on the construction phase of the building.
- B1–B3 and B5 & B7: Use-stage impacts such as maintenance, repair, refurbishment, and operational water use were excluded, as the study aims to isolate the environmental burdens associated with the heating systems only, that under steady state conditions is considered to have a service life and work properly without a need for repair or other until replacement.

Cut-off rules were applied according to EN 15804 requirements. Inputs contributing **less than 1% of total mass or primary energy demand** of the respective module were excluded, provided that the total neglected inputs do not exceed 5% of the total mass and energy per module. Minor materials with negligible mass and environmental relevance were excluded from the inventory. For example: Small plastic parts in radiator systems, Minor fastening elements and Small auxiliary components.

The selection of included materials was based on mass dominance and expected environmental relevance. The main structural materials (steel, aluminum, PEX, insulation materials) represent the majority of the system mass and embodied impacts and were therefore fully included.

Allocation procedures were defined according to **ISO 14044 hierarchy**. In the foreground system, no multi-functional processes were identified. Each component fulfils a single primary function (heating). Therefore, no allocation between co-products was required. For background processes, allocation procedures are handled within the ecoinvent database using the cut-off system model. These allocation rules are embedded in the database and were not modified in this study.

For Module D, the **avoided burden approach** was applied for plastic materials undergoing incineration with energy recovery and metal recycling such as copper, aluminum and steel. This Module is described in detail in further sections.

B. Geographical system boundaries

The geographical system boundaries of the present study were defined in accordance with ISO 14044 and EN 15804 requirements, considering the location of production, installation, use, and end-of-life of the analyzed heating systems. The case study building is located in **Milan, Italy**.

The heating system components (radiators, radiant floor systems, and fan coil units) were assumed to be primarily **manufactured by Italian producers**. However, in cases where specific manufacturing data were unavailable, **European average datasets** were used. Consequently, raw material extraction and material production processes were modeled using European or Italian market datasets available in the ecoinvent database.

Electricity processes were modeled using **Italian or European electricity mixes**, depending on data availability in the database. This ensures consistency with the geographical context of manufacturing and end-of-life treatment.

Similarly, natural gas supply was modeled using Italian or European market datasets. Upstream processes including extraction, processing, and distribution were based on regional average data provided in the ecoinvent database. This ensures consistency between the modeled energy carriers and the geographical context of the case study.

End-of-life processes were modeled according to Italian waste management practices. Recycling, landfill, and incineration processes were based on European or Italian datasets.

C. Temporal system boundaries

The temporal system boundaries of this study are defined as the service life of the analyzed technical components and case study and the time horizon embedded in the selected impact assessment methods.

The **Estimated Service Life (ESL)** of each product was defined individually according to manufacturer specifications and technical standards. Since the analyzed heating systems (radiator, radiant floor, and fan coil systems) consist of multiple components with different durability levels, the ESL varies from product to product. For example, radiators are assumed to have an estimated service life of 20 years, whereas distribution pipes (e.g., PEX piping systems) are assumed to have a service life of 50 years. Similar differentiation applies to other components such as fan coil units, manifolds, valves, and auxiliary equipment. All service life assumptions are explicitly specified in the Life Cycle Inventory (LCI) phase and replacement cycles are modelled accordingly within the reference study period.

The **Reference Study Period (RSP)** of the case study apartment is defined as **50 years**, in accordance with EN 15804 and common practice for residential buildings. The same 50-year period is adopted for the entire assessment of the heating systems, ensuring consistency between building lifetime and system evaluation. Components with a service life shorter than 50 years are modelled with appropriate replacements within the RSP.

In addition to the service life assumptions, temporal aspects are embedded in the Life Cycle Impact Assessment (LCIA) methodology. The climate change impact category is assessed using the **Global Warming Potential** over a **100-year time horizon** (GWP100), as defined by the **IPCC** and implemented in the EF EN 15804 method. Therefore, greenhouse gas emissions are characterized based on their radiative forcing integrated over 100 years. Similarly, ozone depletion is assessed using the Ozone Depletion Potential (ODP), expressed in kg CFC-11 equivalents, based on atmospheric lifetime modelling and long-term stratospheric effects. It should be emphasized that these temporal boundaries refer to the **modelling time horizon of the characterization factors**, and not to the operational lifetime of the building. LCA results represent potential impacts over a standardized time horizon rather than time-resolved environmental damages.

2.2.2.5. Life Cycle Impact Assessment methodology

The life cycle impact assessment was performed using the EN 15804:2019 + A2 methodology, which represents the current reference standard for the environmental assessment of construction products and building-related systems. The impact categories are reported in Table 22 below, classified by: (i) impact category, (ii) category indicator, (iii) unit of measurement, and (iv) whether the impact category is presented as core or additional for the EN 15804: +A2 2019.

Table 22: LCA Impact categories classification

Impact category	**Category indicator**	**Unit**	**EN 15804 + A2**
Acidification	Accumulated exceedance (AE)	mol H+-Eq	Core
Climate change	Global warming potential (GWP100)	kg CO_2-Eq	Core
Climate change - biogenic	Global warming potential (GWP100)	kg CO_2-Eq	Core
Climate change - fossil	Global warming potential (GWP100)	kg CO_2-Eq	Core
Climate change - land use and land use change	Global warming potential (GWP100)	kg CO_2-Eq	Core
Resource use, fossils	Abiotic depletion potential (ADP): fossil fuels	MJ, net calorific value	Core
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P-Eq	Core
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N-Eq	Core
Eutrophication, terrestrial	Accumulated exceedance (AE)	mol N-Eq	Core
Resource use, minerals and metals	Abiotic depletion potential (ADP): elements (ultimate reserves)	kg Sb-Eq	Core
Ozone depletion	Ozone depletion potential (ODP)	kg CFC-11-Eq	Core
Photochemical ozone formation	Tropospheric ozone concentration increases	kg NMVOC-Eq	Core
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq. deprived	Core
Particulate matter	Impact on human health	disease incidence	Additional
Ecotoxicity: freshwater	Comparative toxic unit for ecosystems (CTUe)	CTUe	Additional
Human toxicity, cancer	Comparative toxic unit for human (CTUh)	CTUh	Additional
Human toxicity, non-cancer	Comparative toxic unit for human (CTUh)	CTUh	Additional
Ionizing radiation	Human exposure efficiency relative to U-235	kBq U235-Eq	Additional
Land use	Soil quality index	dimensionless	Additional

2.2.2.6. Data availability and Assumptions

The **Life Cycle Inventory (LCI) data used in this study were primarily derived from technical datasheets provided by manufacturers** of the selected heating system components. These datasheets provided information regarding **material composition, mass per unit, thermal performance characteristics, and expected service life**. When primary manufacturer data were not available, secondary data sources were used. These included: **Environmental Product Declarations (EPDs) compliant with EN 15804**, Peer-reviewed literature and Technical reports and industry guidelines.

Due to limitations in database coverage, not all materials or manufacturing processes could be directly matched to specific datasets within the LCA software. In such cases, **proxy processes** were selected. Proxy selection was based on the following criteria:

- Similarity in material composition,
- Comparable production technology,
- Equivalent geographical context (preferably European datasets),
- Comparable environmental performance characteristics.

The use of proxy datasets introduces uncertainty; however, efforts were made to select the most representative available processes to ensure methodological consistency and transparency.

2.2.2.7. LCA software

The life cycle assessment was carried out using **SimaPro**, a widely used LCA software for modeling and analyzing environmental impacts. The life cycle inventory data were primarily sourced from the **Ecoinvent database,** which has been positively evaluated by the Joint Research Centre (JRC) for its compliance with European LCA methodological standards. Although SimaPro is not specifically developed for the construction sector, it offers a high level of modeling flexibility and transparency, making it particularly suitable for the detailed assessment of building subsystems. In this study, SimaPro was used to model HVAC systems at the component level, including the generation system (boiler), emission systems (radiators), and distribution systems (pipes).

SimaPro is based on **process-oriented inventory databases** rather than predefined Environmental Product Declarations. Therefore, all materials, energy carriers, and industrial processes were **explicitly selected and modelled by the user.** Background life cycle inventory data were sourced from the ecoinvent database (version 3.9.1, allocation cut-off by classification), ensuring consistency, transparency, and **traceability down to the unit process level.**

All relevant life cycle modules were modelled explicitly in accordance with **EN 15804:2019 + A2.** The **product stage (A1–A3)** was modelled by selecting appropriate material production and manufacturing processes. Replacement of HVAC components during the building lifetime was accounted for in **module B4**, while operational energy use was modelled in **module B6**. End-of-life processes were modelled by explicitly defining w**aste treatment (C3) and disposal routes (C4)**. Potential benefits and burdens beyond the system boundary were reported separately in module D.

The modelling of the product stage (modules A1–A3) in SimaPro is based on the material composition of each HVAC component. Manufacturing processes are defined according to the bill of materials, which can be obtained from the scientific literature, manufacturers' technical documentation, and product data sheets, taking into account system sizing and performance requirements. Where available, Environmental Product Declarations (EPDs) are used as a reference for material composition and manufacturing information. In cases where specific manufacturer data are not available, representative values reported in the literature are adopted. The collected data are implemented in SimaPro by selecting appropriate unit processes from the database, with each process linked to the system through inputs to the technosphere.

Module B4 accounts for the **replacement of HVAC components** during the reference service life of the building. The number of replacements for each component is calculated according to the formulation provided in **EN 15978:2011**, based on the defined temporal boundaries of the study.

$$No\ of\ replacement\ (i) = rounded\ (\frac{ReqSL}{ESL(i)} - 1) \tag{24}$$

Where:

- **rounded** indicates rounding to the upper integer, in accordance with the 2011 version of the standard.
- ESL(i), is the estimated service life for the product (i).
- ReqSL, is the required service life of the building.

The resulting replacement factor is applied linearly to the relevant life-cycle modules, including the product stage (A1–A3), end-of-life processes (C3–C4), and benefits and burdens beyond the system boundary (module D).

Module B6 represents the operational phase of the HVAC systems and includes the energy use during the use phase. This module is modelled in SimaPro as an input to the technosphere, corresponding to the consumption of energy carriers such as electricity or natural gas. Country-specific datasets are used to reflect the geographical context of the study.

End-of-life processes are modelled through modules C3 and C4. Module C3 represents waste processing activities, which depend on the material type and typically include sorting and pre-treatment processes prior to final disposal or recovery. At this stage, the quantity of material corresponds to the amount entering the product system. Module C4 represents the final disposal routes, which may include landfill, incineration, or preparation for recycling, depending on the material considered. These processes are modelled in SimaPro as outputs to the technosphere. Emissions to air associated with operational energy use, such as gaseous emissions resulting from fuel combustion in module B6, are also modelled where relevant.

As SimaPro is not specifically developed for construction products, in cases where dedicated processes for specific materials or components are not available in the database, proxy processes representing technologically and compositionally similar materials are selected. This approach ensures the completeness of the life-cycle model while maintaining consistency with the defined system boundaries and methodological assumptions.

2.2.2.8. Module D1

The European standard EN 15804 (2019) defines this module as accounting for the potential benefits or burdens arising from the recycling or reuse of materials, as well as from energy carriers leaving the product system. In general, a negative result indicates the occurrence of an environmental benefit, whereas a positive value represents an environmental load. As this module addresses material and energy recovery, the calculation procedures provided in the standard guidelines are applied.

$$e_{module\ D1.1} = \sum_i (M_{MR\ out}|_i - M_{MR\ in}|_i) * \eta_R * \left(E_{MRafterEoWout}|_i - E_{VMSub\ out}|_i * \frac{Q_{R\ out}}{Q_{Sub}}|_i\right) \quad (25)$$

Where:

- M_{MRout} represents the material sent to recycling at the end of module C3;
- M_{MRin} represents the recycled material that entered the system at the manufacturing phase;
- η_R represents the efficiency of the recycling process.
- $E_{MRafterEow\ out}$ represents the emission factor for the recycling of the material;
- $E_{VMsubout}$ represents the emission factor for the production of virgin material;
- The ratio Q_{Rout} / Q_{sub} the quality of the recycled material is calculated over the quality of the substituted one. The downcycling coefficient aims to reduce the emission factor for the substituted virgin material.

In the adopted formulation, the first term determines the net amount of virgin material directed to recycling. This quantity is multiplied by the emission factor associated with the recycling process. The resulting value is then reduced by the emissions corresponding to the production of the substituted virgin material, adjusted by the downcycling ratio. When the emissions avoided through the substitution of virgin material exceed those generated by the recycling process, the overall result becomes negative, indicating an environmental benefit for the system. For modelling purposes, the material quantity associated with recycling emissions is represented in SimaPro as an "output to technosphere – waste", while the downcycled fraction is modelled as an "avoided product".

In addition to material recycling, benefits and burdens may also arise from the recovery of energy through incineration or landfilling of materials. Certain materials included in the inventory, such as plastics, are partially treated through incineration processes. To quantify the recovered energy in the form of electricity and heat, the equation corresponding to incineration processes is applied. This formulation accounts for the energy recovered during incineration. In SimaPro, the recovered amounts of heat and electricity are modelled by introducing the calculated values into the system as avoided products.

$$e_{module\ D1.3} = -M_{INC\ out} * (LHV * \eta_{INC\ heat} * E_{SE\ heat} + LHV * \eta_{INC\ elec} * E_{SE\ elec}) \quad (26)$$

Where:

- M_{INCout} is amount of waste that will be incinerated with energy recovery efficiency,
- LHV is lower heating value of the material,
- $\eta_{INC\ heat}$ is efficiency of the incineration process for heat,

- $\eta_{INC\ elec}$ is efficiency of the incineration process for electricity,
- $E_{SE\ heat}$, $E_{SE\ elec}$, specific emissions and resources consumed per unit of analysis that would have arisen from specific current average substituted energy source; heat, electricity.

Based on the above equation for Module D and considering that in most of the processes described in the Life Cycle Inventory the materials undergoing incineration with energy recovery are predominantly **plastics**, this formulation is applied to quantify the environmental credits associated with energy recovery.

In this context, the equation is implemented to account for the avoided energy production resulting from the **incineration of plastic materials**. The calculation is performed by incorporating the amount of plastic sent to incineration based on each product amount and adopting a **lower heating value (LHV) of 11 kWh/kg**. The efficiency factor for heat recovery (**$X_{INC\ heat}$**) is assumed to be **0.27**, representing the efficiency of plastic incineration for thermal energy production. Similarly, electricity recovery is calculated using the same lower heating value, with the efficiency factor for electricity generation (**$X_{INC\ elec}$**) assumed to be **0.20**.

The resulting recovered heat and electricity values are modelled in **SimaPro** as avoided products within Module D, representing the substitution of conventional energy production through energy recovery from plastic waste incineration.

2.2.3. Life cycle inventory

Up to this stage of the research, the **goal and scope** of the study have been defined and detailed for the analysis of the HVAC systems of the case-study apartment. In accordance with the principles and guidelines outlined in the international standards **ISO 14044 (2006)** and **EN 15978**, it is now necessary to present and examine the **Life Cycle Inventory (LCI) phase**.

As described by Hauschild, the inventory phase is driven by the preceding phases of the LCA. Its objective is to collect and quantify data related to the **elementary flows** associated with the processes included within the product system. The Life Cycle Inventory can be defined as a *"list of quantified elementary flows crossing the system boundary"* [43]

This chapter begins with a brief description of the **building characteristics and climatic context**, followed by a detailed definition of the **HVAC systems** and their internal components. These components are subsequently described in terms of their **manufactured materials and required quantities** for the case-study apartment, as defined in the previous section related to the energy modelling and system design phase.

At this stage, the inventory modeling was structured by identifying the unit processes associated with each material composing the HVAC components. For each material input, the corresponding background processes available in the ecoinvent database were selected and linked within SimaPro. The modeling approach follows a cradle-to-cradle system boundary, ensuring that upstream processes (raw material extraction and manufacturing), as well as downstream processes (end-of-life treatment and recycling), are consistently included. Data on material composition and manufacturing processes were primarily obtained from technical datasheets and Environmental Product Declarations (EPDs), either provided directly by manufacturers or sourced from comparable studies on similar products. These intermediary flows (material quantities per functional unit) were then associated with the relevant unit processes to allow the calculation of the corresponding elementary flows (emissions and resource extractions).

Given the complexity of HVAC components, which may consist of numerous materials and multiple production stages, the inventory analysis at this level focuses specifically on the material-related contributions within the modules. Particular attention was given to the main constituent materials, as these typically dominate the aggregated environmental impacts. In cases where detailed information on material composition or percentage shares was not available from manufacturers, appropriate assumptions were made based on peer-reviewed literature and recognized databases. All assumptions and data sources were documented to ensure transparency and consistency. Further clarification of these assumptions is provided in the following sections. Should further detailed information regarding each system's components be required, the relevant inventory data can be found in the final section of the Annex.

2.2.3.1. Case study & climate

The residential apartment selected as the case study in this research serves as a **reference unit for the Life Cycle Inventory (LCI) analysis** of three alternative HVAC emission systems: **radiators, fan coils, and radiant floor heating**. The apartment is used as a controlled and identical physical context in which these emission systems can be sized, quantified, and compared on a consistent basis. All systems are designed to meet the same space-heating energy demand of the dwelling, ensuring that differences in material requirements, component sizing, and associated life-cycle flows arise exclusively from the characteristics of the emission systems themselves.

To maintain comparability at the inventory level, all emission systems are coupled with the **same type of heat generation system**, namely a **natural gas condensing boiler**. The boiler is treated as an identical upstream energy source for all configurations, supplying the required thermal energy under the same operating conditions. Variations in system performance and resulting inventory flows are therefore attributable to the different emission technologies, which operate at different supply temperatures and efficiencies, rather than to differences in energy generation.

The sizing of all HVAC systems and the determination of the required technical dimensions and quantities were performed during the **design phase**, as presented in the previous chapter dedicated to the **energy modelling of the case-study building**. These results form the quantitative basis for the inventory analysis, ensuring that all material inputs and component specifications used in the LCI are directly derived from consistent and previously validated energy simulations.

The geometric characteristics of the apartment, including **floor area, room layout, volumes, and façade orientations**, are kept constant across all system configurations. These fixed building properties define a common basis for the sizing of HVAC components and the quantification of material inputs in the inventory phase. Similarly, all simulations and inventory calculations are performed under **identical climatic conditions**, using a representative climate dataset corresponding to **Milan, Italy**, classified as **Climate Zone 4A**. This ensures that heating demand, system sizing, and material quantities are evaluated consistently for a single climatic context, eliminating climate-related variability from the comparison.

For the purposes of the Life Cycle Assessment, a **reference study period of 50 years** is adopted, in line with common practice in building LCA studies. In addition, the **required service life of the building** is assumed to be **50 years** for the case study. These values are used consistently for the calculation of component service lives and the determination of replacement cycles within the inventory and subsequent life cycle modules.

By adopting this approach, the case-study apartment functions as a **neutral and consistent framework** for the Life Cycle Inventory of HVAC emission systems, allowing a transparent comparison of material flows, component composition, and life-cycle impacts associated with radiators, fan coils, and radiant floor heating under equivalent energy demand and boundary conditions.

2.2.3.2. HVAC systems & Functional unit

In the following sections, the **components of the HVAC systems** are described in detail. Each component is presented in alignment with the **selected manufacturer data** and the **quantified amounts** derived from the system design and energy modelling phase. The Life Cycle Assessment is structured in accordance with **EN 15804**, covering all relevant modules from **Module A1–A3** through to the potential benefits and loads accounted for in **Module D**.

The **radiator system** comprises radiators, distribution pipes, a manifold, and the boiler. The **radiant floor system** consists of radiant floor pipes, the manifold, the main distribution pipe connecting the boiler to the manifold, and the boiler. The **fan coil system** includes fan coil units, distribution pipes, the manifold, and the boiler. In addition, for both the radiant floor and fan coil configurations, an **auxiliary towel dryer** is included in the bathroom to provide towel drying functionality and supplementary space heating. The component has been designed to operate for a duration of three and a half hours per week during the heating season, which spans a total of 181 days per year.

Table 23: All systems calculated energy emitted for the case study during RSP

System	Energy emitted for SH (during RSP)	Additional energy emitted in the towel warmer	Total	Unit
Radiators	113.8	-	113.8	MWh_{th}
Radiant floor	117.0	0.8	117.8	MWh_{th}
Fancoils	111.0	0.8	111.8	MWh_{th}

The values presented in Table 23 represent the **total energy emitted over the entire reference service period (RSP)** of the HVAC systems for the case study building. These values were obtained from the dynamic energy modelling results and account for all energy required to operate each system configuration during its lifetime.

For the radiant floor and fan coil configurations, the system boundary includes both **space heating and the auxiliary towel dryer used for cloth drying in the bathroom**. Therefore, the total energy emitted of each system considers the combined operation of the **boiler, emission units, and the towel dryer**, depending on the system configuration.

To ensure consistency with the defined functional unit, an **energy balance approach** is applied. The total energy consumption of each system is related to the useful thermal energy delivered to the conditioned zone. This relationship is expressed as:

$$W_{RF} = \frac{W_{boiler} + W_{fan\ coils} + W_{towel\ dryer}}{Q_{emitted,fan\ coils} + Q_{emitted,towel\ dryer}} \tag{27}$$

where the numerator represents the **total energy consumed by the system components**, and the denominator represents the **useful thermal energy emitted to the indoor space and for towel drying**.

For the configurations including a towel dryer (radiant floor and fan coil systems), it is assumed that **the thermal energy emitted by the towel dryer is equal to its electricity consumption**. This assumption reflects the direct conversion of electrical energy into heat by the electric resistance element of the towel dryer.

During the **Life Cycle Inventory (LCI) modelling**, this formulation is used to **normalize all inventory data to the functional unit of 1 kWh of delivered thermal energy**. In this way, the material and energy flows associated with each HVAC configuration are scaled according to the energy required to deliver the same amount of useful heat.

This normalization step ensures that the environmental impacts of the different systems can be **directly compared on an equivalent functional basis**, allowing a consistent evaluation of the radiator, radiant floor, and fan coil systems within the LCA framework.

Following this normalization step, the **material composition and inventory data of each HVAC system component** are described in detail in the following sections.

2.2.3.3. Radiators

Based on the results obtained from the energy modelling and system design phase, **four radiators** are required for this configuration, with one unit installed in each of the following spaces: the **kitchen, living room, bathroom, and bedroom**.

In accordance with the system sizing performed during the energy modelling phase, the selected radiator model is manufactured by **Stelrad**. The specific product chosen is the **Classic Column Horizontal radiator**, type **UIN 163019**, finished in **RAL 9010 (Pure White)**. The radiators feature a **three-column configuration**, with a **height of 500 mm**, a **length of 1042 mm**, and **22 elements**. Based on the manufacturer's technical data, the declared mass is **26.09 kg per meter**, resulting in a **total weight of 27.19 kg per radiator** for the selected dimensions.

Although the manufacturer datasheet provides extensive technical and installation information, the Life Cycle Assessment at the inventory level focuses primarily on the **material composition and total mass** of the radiators. For the selected model, the radiator body is manufactured entirely from **steel**, in compliance with **UNI 442**, and is finished with a **satin paint coating**, which applies to all available RAL colour options, including RAL 9010. Consequently, steel is considered the dominant material for the radiator component in the LCI.

Regarding service life assumptions, the manufacturer specifies a **warranty period of five years** for the radiator product . However, based on evidence from the literature related to building Life Cycle Assessment, radiators typically exhibit significantly longer operational lifetimes, often exceeding ten years, depending on factors such as water quality, corrosion risk, and maintenance conditions. For the purposes of this study, a **service life of 20 years** is assumed for the radiators and applied consistently within the inventory and subsequent life cycle impact assessment. [36]

Table 24: Radiators inventory data

Material	Value	Unit	Selected Process
Module A1-3			
Steel	108.76	kg /4 radiators	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U
Paint (Satin)	9.96	m^2/4 radiators	Powder coat, steel {RER}| powder coating, steel | Cut-off, U
Module C3			
Steel- sorting	100	%	Iron scrap, sorted, pressed {Europe without Switzerland}| treatment of metal scrap, mixed, for recycling, unsorted, sorting | Cut-off, U
Module C4			
Steel to Landfill	3	%	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U
Steel to recycling	97	%	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U

The radiator paint is considered exclusively as a coating application process and is therefore included only within **Module A1–A3**. To calculate the amount of paint required, the **heated surface area of the radiator was derived from the manufacturer's datasheet**, with a value of **2.39 m^2/m**. This value was then multiplied by the length of each radiator, resulting in a **coated surface area of 2.49 m^2 per radiator** considered in this process.

It is worth noting that, in practice, **coatings are generally not removed prior to recycling**. Consequently, the organic components of the paint are **combusted during the remelting process** and are therefore accounted for within the secondary metal production.

The same processes were also included in **Module B4**, scaled by multiplying the calculated number of replacements for this specific product over the reference service life.

Module D accounts for the recycling of steel radiators. As described in the previous sections and in accordance with the applied formula, it is assumed that **50 % of the steel used in the manufacturing of the radiators originates from recycled material**, which directly affects the MMR_{in} term in the equation. Furthermore, as reported in the table above, **97 % of the steel content is assumed to be recycled at end of life**, thereby contributing to the credits and benefits accounted for in Module D.

For this assessment, the **quality ratio is assumed to be equal to 1**, indicating no quality loss between the recycled and substituted material. In addition, the **efficiency of the steel recycling process is assumed to be 81 %** for this stage.

The recycling process representing the avoidance of virgin material production, and therefore used for the avoided product in SimaPro, is modeled using the dataset *"Steel, low-alloyed {GLO} | market for steel, low-alloyed | Cut-off, U"*.

2.2.3.4. Radiant floor pipes

The next component considered in the Life Cycle Inventory is the **radiant floor heating pipe system**, which constitutes the primary heat emission element of the floor heating configuration. The pipes are manufactured from **cross-linked polyethylene (PEX-a)** produced using the **peroxide cross-linking**

method and are equipped with an **oxygen anti-diffusion barrier**, in accordance with the requirements of the European standard **EN 1264-4** [39].

The selected product is manufactured by **Danfoss** and is commercially identified as **FH PEX-a pipes**, specifically designed for hydronic floor heating applications. Based on the system design and sizing results obtained in the energy modelling phase, a total pipe length of **221.2 m** with a nominal dimension of **16 × 2 mm** is required for the case-study apartment. The pipes are installed starting from the manifold and distributed across the heated floor areas of the dwelling according to the designed layout.

For the purpose of the Life Cycle Assessment, the **mass of the pipes** is required to quantify the material flows implemented in **SimaPro**. Although the product datasheet does not directly report the pipe mass, information provided on the manufacturer's website indicates a weight of **0.092 kg/m**. Based on this value, the total mass of radiant floor pipes required for the system amounts to **20.35 kg** [44].

With respect to service life, no explicit value is specified in the product datasheet. However, based on reference literature, including an **Environmental Product Declaration (EPD) for PEX pipe systems by TEPPFA** and a study by **Lorente López** on the life cycle of materials used in radiant floor heating systems, the service life of PEX pipes compliant with **EN 1264** is commonly assumed to be **50 years** under normal operating conditions, with supply temperatures up to **70 °C**. As this service life corresponds to the full reference study period adopted in this research, **no replacement (Module B4)** is considered for the radiant floor pipes.[45], [46]

Regarding end-of-life scenarios, and based on the same EPD references, cross-linked polyethylene pipes are assumed to be **non-recyclable** under current average market conditions. Accordingly, the end-of-life treatment is modelled as **85% landfill disposal** and **15% incineration**, with the latter generating environmental credits from energy recovery that partially offset the impacts associated with material production [45]. Although recent pilot projects have demonstrated the technical feasibility of chemical recycling of PEX pipes, such technologies are not yet widely implemented. Therefore, they are not considered in the present LCA, which follows **current market-average end-of-life practices** [47]

Table 25: Radiant floor pipes inventory data

Material	Value	Unit	Selected Process
Module A1-3			
PEX-a pipe, 5-layer with EVOH oxygen barrier (16×2.0 mm)	20.35	kg / total pipe	Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate | Cut-off, U
Module C3			
PEX to waste processing (incineration)	15	%	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration FAE | Cut-off, U
Module C4			
PEX to landfill	85	%	Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, U

For **Module D**, the environmental credits associated with the **incineration of PEX pipes** are accounted for by treating the material as part of the **plastic waste stream**. The calculation of these credits follows the formulation previously introduced for Module D. In accordance with this approach, a **lower heating value (LHV)** of **11 kWh/kg** is assumed for the PEX material. The **efficiency of the incineration process** is taken as **0.27 for heat recovery** and **0.20 for electricity generation**.

Based on these parameters, the corresponding energy recovery values are calculated using the Module D equation and implemented in **SimaPro** as avoided energy production processes. Specifically, the recovered thermal energy is modelled using the process *"Heat, district or industrial, natural gas {RER} | market group for heat, district or industrial, natural gas | Cut-off, U"*, while the recovered electrical energy is represented by the process *"Electricity, medium voltage {IT} | market for electricity, medium voltage | Cut-off, U"*. These processes reflect the substitution of conventional energy production through energy recovery from waste incineration and are included as credits within Module D.

2.2.3.5. Fan coil units

For the **fan coil heating system**, three fan coil units are assigned as the heat emission system based on the results obtained during the **design and sizing phase** of the energy modelling. The selected units are manufactured by **Carisma Sabiana**, with the specific model identified as **CRC 13**. The fan coils are **floor-standing units** of type **MO/MVB**, equipped with a **three-row heat exchanger**. According to the manufacturer's technical datasheet, the **net weight of each unit** is **13 kg**.[40]

Due to the absence of a detailed **bill of materials** in the manufacturer's documentation, the Life Cycle Inventory for the fan coil units is based on the **total declared mass** combined with material composition data sourced from the literature. In particular, the study by **Perk** provides a **process tree for a comparable fan coil convector**, whose material composition is consistent with the technical characteristics of the selected unit. This literature source is therefore used to define the **percentage contribution of each material** within the fan coil unit. The material shares reported in the literature are subsequently **scaled to the manufacturer-declared unit mass**, allowing the mass of each constituent material to be quantified. Detailed information on material types and corresponding masses is provided in the relevant table.[11]

With respect to service life, a **typical operational lifetime of 20 years** is assumed for the fan coil units, in line with common practice for this type of HVAC equipment. At the end of life, the fan coil units are assumed to be **dismantled** and treated as **HVAC/WEEE equipment**. The **steel, aluminum, and copper components** are assumed to be recovered and recycled, reflecting standard European practices for metal-rich building services equipment. In contrast, **plastic components**, including the condensate tray, filter media, and minor fan-related parts, are assumed to be treated as mixed plastic waste and disposed of through **incineration with energy recovery or landfill**.

The same processes were also included in **Module B4**, scaled by multiplying the calculated number of replacements for this specific product over the reference service life.

Table 26: Fan coils inventory data

Material	Value	Unit	Selected Process
Module A1-3			
Steel	31.17	kg / 3 fancoils	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U
Copper	0.9	kg / 3 fancoils	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U
Aluminum	1.5	kg / 3 fancoils	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U
Plastics (pp/pvc)	5.43	kg / 3 fancoils	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U
Module B6			
Electricity	4854.924	MJ over 50 years	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, U
Module C3			
Steel- sorting	100	%	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U
Copper-sorting	100	%	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U
Aluminum-sorting	100	%	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U
Plastics (pp/pvc)-incineration	100	%	Waste polypropylene {CH}| treatment of waste polypropylene, municipal incineration FAE | Cut-off, U
Module C4			
Steel to Landfill	3	%	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U
Steel to recycling	97	%	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U
Copper to Landfill	3	%	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U
Copper to recycling	97	%	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U
Aluminum to Landfill	3	%	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U
Aluminum to recycling	97	%	Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, U

Although **Module B6** was not considered for the radiator and radiant floor systems—where energy use is attributed exclusively to the boiler—fan coil units require **additional electricity consumption** for fan operation. Therefore, in addition to the boiler-related energy use, **Module B6 is also included for the fan coil system**. The electricity demand for fan operation is derived from the energy modelling results and amounts to **26.97 kWh/m²·year**. This value is converted to **MJ** over a **50-year reference study period** and scaled according to the apartment floor area. The resulting energy consumption values are reported in the corresponding table.

In the **ecoinvent database**, certain end-of-life processes required for **copper**, specifically those related to **sorting, landfill disposal, and recycling**, were not available at the level of detail required for this study. Given that the technological structure and treatment pathways of these processes are comparable to those applied to **steel** in the database, the corresponding **steel processes were adopted as proxies** for copper in these cases. This substitution was applied consistently across the inventory modelling and is reflected in the processes reported in the corresponding table.

For **Module D**, the same approach described in the dedicated Module D section is applied, accounting for both **metal recycling** and **energy recovery from plastic incineration**. The avoided product calculations for recycled metals reflect the substitution of virgin material production, assuming a **quality ratio equal to 1**. The processes used to model avoided production for steel, copper, and aluminum, as well as the recovery of heat and electricity from plastic incineration, are presented in the relevant table. Within the Module D equation, the **recycled content of metals used in the manufacturing of fan coil units** is assumed to be **50% for steel**, **10% for copper**, and **20% for aluminum**, respectively.

Table 27: Fancoils module D used processes

Material	Process
Steel	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U
Copper	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U
Aluminum	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U
Electricity	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, U
Heat	Heat, district or industrial, natural gas {RER}| market group for heat, district or industrial, natural gas | Cut-off, U

2.2.3.6. Towel Dryer

A **towel dryer** is included in the **radiant floor** and **fan coil** system configurations as an auxiliary component installed in the bathroom, serving primarily for towel drying and providing limited supplementary space heating. The selected product is an **electric towel heater**, chosen specifically for its intended functional role in these two HVAC configurations.

The towel dryer is manufactured by **LARIS**, with the selected model identified as **Comfort 500 × 900**. The unit is **wall-mounted** and has a **rated electrical power of 170 W**. According to the manufacturer's technical specifications, the towel dryer has overall dimensions of **500 × 900 mm**, a **net weight of 7 kg**, and a **gross weight of 8 kg**. The main structural body is manufactured from **stainless steel**, while minor components such as electrical wiring and cables consist of **plastic materials**. [41], [48]

For **Module B6**, the operational electricity consumption of the towel dryer is assumed to be **170 kWh/year**, corresponding to a typical usage pattern of approximately **three hours per week,** working within the same seasons of heating systems. With respect to service life, the technical lifetime of the towel dryer is assumed to be **15 years**. Based on this lifetime, replacement is accounted for in **Module B4**, with the number of replacements determined over the reference study period and modelled using the same process assumptions applied.

For **Module D**, the environmental benefits associated with material recycling are calculated using the same equation described previously. The recycling of stainless steel is modelled in **SimaPro** using the process *"Steel, low-alloyed {GLO} | market for steel, low-alloyed | Cut-off, U"*, representing avoided production of virgin steel.

Table 28: Towel dryers inventory data

Material	Value	Unit	Selected Process
Module A1-3			
Steel	7	kg / towel dryer	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U
Module B6			
Electricity	769	kWh over 50 years	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, U
Module C3			
Steel- sorting	100	%	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U
Module C4			
Steel to Landfill	3	%	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U
Steel to recycling	97	%	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U

2.2.3.7. Pipes- hydronic distribution system

The **hydronic distribution system** consists of water pipes and a manifold that act as the connection between the heat generation unit and the emission components of each HVAC configuration, namely **radiators, radiant floor heating, and fan coil units**. This subsection focuses specifically on the **water distribution pipes**. It should be noted that this piping system is present in all three HVAC configurations; however, due to differences in system layout and sizing, the **total pipe length varies between systems**. The required pipe lengths for each configuration are derived from the energy modelling and system design phase, while all other characteristics of the piping system remain identical across the three systems.

Table 29: Distribution pipes length used in each system

System	Pipe Length	Unit	comments
Radiators	62.68	m	Pipes from Boiler to Manifold and from Manifold to Radiators
Radiant Floor	1.2	m	Pipes from Boiler to Manifold
Fancoils	48.32	m	Pipes from Boiler to Manifold and from Manifold to Fan coils

The pipes are manufactured by **Giacomini**, with the selected product identified as **R999L**, which is suitable for hydronic heating applications. These **multilayer pipes** consist of an **inner PEX-b layer**, a **central aluminium layer**, and an **outer white PEX-b layer**. The aluminium layer provides an effective barrier against oxygen diffusion and other gases, in addition to offering high resistance to mechanical damage.

According to the manufacturer, these multilayer pipes are suitable for domestic water, heating, and cooling systems and comply with the requirements of **EN 21003** [37]. The selected pipe dimension is **20 × 2 mm**, combined with an **insulation thickness of 13 mm**.

The pipe insulation is composed of **closed-cell polyethylene foam**, protected by a dedicated external film. Based on the manufacturer's technical data, the **total mass of the pipe including insulation** is **190 g/m**, while the mass of the pipe without insulation is **156 g/m**, resulting in an insulation mass of **34 g/m**.

With respect to material composition, the manufacturer datasheet does not explicitly report the mass contribution of the aluminium layer within the pipe. Therefore, information from the literature was used to estimate material fractions. According to specifications reported in **ASTM F1281** for cross-linked **PEX/Al/PEX pipes** of comparable dimensions, the aluminium layer thickness is **0.23 mm**. By adopting typical material densities of **2700 kg/m³ for aluminium** and **950 kg/m³ for PEX**, the aluminium mass fraction is estimated to be **27%** of the pipe mass. Based on this assumption, the aluminium content is calculated as **42.1 g/m**, while the remaining **113.9 g/m** is attributed to PEX [49].

Table 30: Distribution pipes inventory data

Material	Value	Unit	Selected Process
Module A1-3			
(PEX) Crosslinked polyethylene	0.1139 *pipe length per system	kg / total pipes	Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate | Cut-off, U
Aluminum	0.042 *pipe length per system	kg / total pipes	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U
insulation - Expanded polyethylene (PE-LD) foam insulation	0.034 *pipe length per system	kg / total pipes	Polyethylene, linear low density, granulate {RER}| polyethylene production, linear low density, granulate | Cut-off, U
Module C3			
(PEX) Crosslinked polyethylene to incineration	15	%	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration FAE | Cut-off, U
Aluminum-sorting	100	%	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U
insulation - Expanded polyethylene (PE-LD) foam insulation to incineration	15	%	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration FAE | Cut-off, U
Module C4			
(PEX) Crosslinked polyethylene to Landfill	85	%	Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, U
Aluminum to Landfill	100	%	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U
insulation - Expanded polyethylene (PE-LD) foam insulation to Landfill	85	%	Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, U

For the implementation of **Module A1–A3** in the Life Cycle Assessment, the material-specific mass values are multiplied by the system-dependent pipe lengths derived from the energy modelling results for each HVAC configuration. According to the manufacturer datasheet, the estimated **service life of the pipes is 50 years**, which corresponds to the reference study period adopted in this research; therefore, **no replacement is considered in Module B4**.

Regarding end-of-life treatment, the manufacturer specifies that the product should not be disposed of as municipal waste and should instead be collected through dedicated recycling platforms. However, no detailed information is provided on the applicable treatment processes or material-specific recovery rates. Consequently, end-of-life assumptions are based on literature sources, specifically the **TEPPFA EPD for PEX pipe systems**, which reports negligible mechanical recycling and predominantly disposal through **landfill and incineration with energy recovery**. In line with this reference, a similar end-of-life pathway is assumed in the present study. [45]

For **Module D**, the environmental credits associated with the **incineration of PEX pipes and insulation foam** are accounted for by treating the materials as part of the **plastic waste stream**. The calculation of these credits follows the formulation previously introduced for Module D.

Based on these parameters, the corresponding energy recovery values are calculated using the Module D equation and implemented in **SimaPro** as avoided energy production processes. Specifically, the recovered thermal energy is modelled using the process *"Heat, district or industrial, natural gas {RER} | market group for heat, district or industrial, natural gas | Cut-off, U"*, while the recovered electrical energy is represented by the process *"Electricity, medium voltage {IT} | market for electricity, medium voltage | Cut-off, U"*. These processes reflect the substitution of conventional energy production through energy recovery from waste incineration and are included as credits within Module D.

2.2.3.8. Manifold - hydronic distribution system

The second component of the **hydronic distribution system** is the **manifold**, which is installed in all three HVAC configurations considered in this study and is identical in design and specification across the systems. The selected manifold is manufactured by **CALEFFI** and belongs to the **662 series**, identified as type **01180**, designed specifically for heating system applications. The chosen configuration consists of **four outlets**, corresponding to product code **6626D5**. [38]

According to the manufacturer's datasheet, the total mass of the manifold assembly is **3.022 kg**. The declared material composition includes predominantly **brass**, complemented by **steel brackets**, as well as components made of **EPDM** and **polycarbonate**. For the purposes of the Life Cycle Assessment and to maintain modelling simplicity, the manifold is represented using aggregated material groups, namely **brass**, **steel**, and **polymers**. Minor components such as stainless steel springs, elastomeric seals, and small plastic parts are not explicitly modelled.

Based on the material characteristics of the product and its typical construction, the mass composition of the manifold is assumed to consist of **90% brass**, **7% steel**, and **3% polymers**, relative to the total weight. Brass components in hydronic systems are generally characterised by long operational lifetimes under indoor conditions, typically ranging between **40 and 60 years**. Accordingly, no replacement of the brass manifold body is assumed over the reference study period. In contrast, polymeric components are assumed to require replacement every **20 years**, reflecting their comparatively shorter service life.

Table 31: Manifolds inventory data

Material	Value	Unit	Selected Process
Module A1-3			
Steel	0.21	kg / manifold	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U
Brass	2.72	kg / manifold	Brass {CH}| market for brass | Cut-off, U
Polymer	0.09	kg / manifold	Polycarbonate {RER}| market for polycarbonate | Cut-off, U
Module C3			
Steel- sorting	100	%	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U
Brass-sorting	100	%	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U
Polymer to incineration	100	%	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration FAE | Cut-off, U
Module C4			
Steel to Landfill	3	%	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U
Steel to recycling	97	%	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U
Brass to Landfill	5	%	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U
Brass to recycling	95	%	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U

As already mentioned for previous components, some materials do not have explicitly defined processes for certain life cycle modules. In the case of the **manifold component**, the **sorting process for Module C3** and the **end-of-life processes for Module C4** were not available for **brass**. Therefore, given that the treatment processes are comparable to those of **steel**, the corresponding **steel processes were used as proxies** for these modules for this material.

At the end of life, the brass content of the manifold is assumed to be **fully recyclable**, in line with common European practices for copper alloy components compliant with relevant EN standards. A **recycling efficiency of 95%** is applied, with the remaining fraction assumed to be disposed of via landfill. Polymeric components are aggregated and modelled using a **polycarbonate (PC) market dataset for Europe**, selected as a representative engineering thermoplastic commonly used in HVAC applications. This dataset reflects **virgin material supply**, thereby constituting a conservative modelling assumption.

As previously stated, the manifold is composed primarily of **brass**, with minor components made of **steel** and **plastics**. While brass is assumed to have a long service life, **Module B4** is applied to the steel and plastic components in accordance with their shorter expected lifetimes. These steel and plastic parts are therefore assumed to be **replaced every 20 years**, using the same processes for both manufacturing and end-of-life treatment as those applied to the initial components.

Module D is modelled following the same equations described previously for this module, accounting for the **recycling of brass and steel**, with recycling rates of **95%** and **97%**, respectively. These recycling rates are applied to quantify the environmental credits associated with the avoidance of virgin material production. In addition, plastic components are considered for **energy recovery through incineration**, in line with the assumptions adopted for other plastic materials in the study.

Table 32: Manifold Module D used processes in sima pro

Material	Process
Steel	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U
Brass	Brass {CH}| market for brass | Cut-off, U
Electricity	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, U
Heat	Heat, district or industrial, natural gas {RER}| market group for heat, district or industrial, natural gas | Cut-off, U

2.2.3.9. Boiler- the generation system

The final component addressed in the Life Cycle Inventory is the **heat generation system**, which is common to all three HVAC configurations considered in this study. As the primary objective of the assessment is to evaluate the environmental impacts associated with **emission and distribution systems**, a **single, identical heat generation system** is assumed for all configurations in order to ensure comparability. For this purpose, a **natural gas condensing boiler** installed within the case-study apartment is considered.

The technical characteristics of the boiler are identical across all configurations. However, differences arise in the **operational efficiency** and **energy demand** associated with each system, as determined during the energy modelling phase. These variations are reflected in the energy consumption values attributed to the boiler for each configuration. Prior to detailed modelling of the boiler in **SimaPro**, a summary of the **boiler efficiency and corresponding energy demand** for each system is provided, based on the results obtained in the energy modelling section.

Table 33: Boiler efficiency and energy required of each system

System	Energy Needs	Unit	Boiler Efficiency (%)
Radiators	27.42	$kWh_{th} / m^2.y$	90
Radiant Floor	28.19	$kWh_{th} / m^2.y$	95
Fancoils	26.75	$kWh_{th} / m^2.y$	92

The selected boiler is manufactured by **IMMERGAS**, with the specific model identified as **VICTRIX TERA VIP V2**. According to the manufacturer's datasheet, the total mass of the boiler is **43.7 kg**. The material composition of the boiler is defined within **Module A1–A3**, as reported in the corresponding inventory data.

An **estimated service life of 21 years** is assumed for the condensing boiler, in line with typical values reported for this type of equipment. Accordingly, replacement is accounted for in **Module B4** by applying the same modelling approach used for other components requiring replacement over the reference study period [42].

Table 34: boiler Inventory Data

Material	Value	Unit	Selected Process
Module A1-3			
Steel	30.59	kg / boiler	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U
Copper	4.37	kg / boiler	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U
Aluminum	5.24	kg / boiler	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U
Plastics (pp/pvc)	3.5	kg / boiler	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U
Module B6			
Natural gas	-	MJ over 50 years	Natural gas, low pressure {IT}| market for natural gas, low pressure | Cut-off, U
Module C3			
Steel- sorting	100	%	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U
Copper-sorting	100	%	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U
Aluminum-sorting	100	%	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U
Plastics (pp/pvc)-incineration	100	%	Waste polypropylene {CH}| treatment of waste polypropylene, municipal incineration FAE | Cut-off, U
Module C4			
Steel to Landfill	3	%	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U
Steel to recycling	97	%	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U
Copper to Landfill	3	%	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U
Copper to recycling	97	%	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U
Aluminum to Landfill	3	%	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U
Aluminum to recycling	97	%	Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, U

As shown in the inventory summary, no direct value is reported for **natural gas consumption** within the initial material inventory, as gas use varies between systems. Therefore, natural gas consumption is modelled separately for each configuration based on the **system-specific energy demand**, **boiler efficiency**, **apartment floor area**, and a **50-year reference study period**. The combustion of natural gas is represented by emissions to the technosphere, including **carbon dioxide (CO_2)**, **carbon monoxide (CO)**, and **nitrogen oxides (NO_x)**, which are accounted for in the corresponding life cycle modules.

Table 35: Module B6 inventory data of boilers in each system

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
Radiator System					
B6	Natural gas	ecoinvent process	Natural gas, low pressure {IT}| market for natural gas, low pressure | Cut-off, U	MJ / fU	4.00E+00
B6	Carbon dioxide, fossil	elemenary flow	Carbon dioxide, fossil	kg / fU	2.16E-01
B6	Carbon monoxide, fossil	elemenary flow	Carbon monoxide, fossil	kg / fU	1.67E-05
B6	Nitrogen oxides	elemenary flow	Nitrogen oxides, IT	kg / fU	2.67E-05
Radiant Floor System					
B6	Natural gas	ecoinvent process	Natural gas, low pressure {IT}| market for natural gas, low pressure | Cut-off, U	MJ / fU	3.76E+00
B6	Carbon dioxide, fossil	elemenary flow	Carbon dioxide, fossil	kg / fU	2.04E-01
B6	Carbon monoxide, fossil	elemenary flow	Carbon monoxide, fossil	kg / fU	1.57E-05
B6	Nitrogen oxides	elemenary flow	Nitrogen oxides, IT	kg / fU	2.51E-05
Fancoil System					
B6	Natural gas	ecoinvent process	Natural gas, low pressure {IT}| market for natural gas, low pressure | Cut-off, U	MJ / fU	3.89E+00
B6	Carbon dioxide, fossil	elemenary flow	Carbon dioxide, fossil	kg / fU	2.10E-01
B6	Carbon monoxide, fossil	elemenary flow	Carbon monoxide, fossil	kg / fU	1.62E-05
B6	Nitrogen oxides	elemenary flow	Nitrogen oxides, IT	kg / fU	2.59E-05

In the **ecoinvent database**, certain end-of-life processes required for **copper**, specifically those related to **sorting, landfill disposal, and recycling**, were not available at the level of detail required for this study. Given that the technological structure and treatment pathways of these processes are comparable to those applied to **steel** in the database, the corresponding **steel processes were adopted as proxies** for copper in these cases. This substitution was applied consistently across the inventory modelling and is reflected in the processes reported in the corresponding table.

For **Module D**, the same approach described in the dedicated Module D section is applied, accounting for both **metal recycling** and **energy recovery from plastic incineration**. The avoided product calculations for recycled metals reflect the substitution of virgin material production, assuming a **quality ratio equal to 1**. The processes used to model avoided production for steel, copper, and aluminum, as well as the recovery of heat and electricity from plastic incineration, are presented in the relevant table. Within the Module D equation, the **recycled content of metals used in the manufacturing of fan coil units** is assumed to be **50% for steel**, **10% for copper**, and **20% for aluminum**, respectively.

Table 36: Boilers module D used processes in sima pro

Material	Process
Steel	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U
Copper	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U
Aluminum	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U
Electricity	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, U
Heat	Heat, district or industrial, natural gas {RER}| market group for heat, district or industrial, natural gas | Cut-off, U

Up to this point in the Life Cycle Assessment, the **Goal and Scope** and **Life Cycle Inventory** phases have been presented. These sections have outlined the rationale for conducting the study and defined key parameters, including the **functional unit**, the **case study** used for the assessment, the **system boundaries**, and the **tools adopted** for the analysis. Before proceeding to the next phase, which presents the **Life Cycle Impact Assessment and the results of the modelling in SimaPro**, it is important to highlight several aspects of the inventory modelling.

As the objective of the study is to assess **emission and distribution systems**, the **heat generation system** is kept identical across all configurations. However, **energy consumption differs between systems**, which directly influences **Module B6** for each configuration. A variety of materials are involved in the manufacturing phase, predominantly **steel, plastics, aluminium, and copper**. The **service life of each component** represents a key parameter, as it determines the number of replacements accounted for in **Module B4**, thereby affecting the overall assessment. In addition, **end-of-life treatments** vary across materials and may result in **recycling credits in Module D**, depending on the recycling efficiency associated with each material.

In the following section, the results are presented for the three HVAC system configurations considered in this study: the **radiator system**, consisting of four radiators, distribution pipes, a manifold, and a boiler; the **radiant floor system**, comprising radiant floor pipes, a manifold, the main distribution pipe, a boiler, and a towel dryer; and the **fan coil system**, consisting of three fan coil units, distribution pipes, a manifold, a boiler, and a towel dryer. The assessment is conducted using the defined **functional unit** to ensure comparability across systems, considering that each configuration delivers **1 kWh of thermal energy** to the case study over the **50-year reference study period**, based on the materials and components included in each system.

2.2.4. Life Cycle Impact Assessment

Now that the **Life Cycle Inventory phase** has been completed, all relevant details have been modelled in **SimaPro**, and the results have been generated, the next section presents the findings based on the **Life Cycle Impact Assessment**.

The Life Cycle Impact Assessment (LCIA) phase translates the inventory results (LCI) into potential environmental impacts by assigning emissions and resource uses to specific impact categories and applying scientifically derived characterization factors. According to ISO 14044 and the EF EN 15804 method adopted in this study, the assessment is performed at **midpoint level**. **Midpoint indicators represent specific environmental phenomena, such as Climate Change or Acidification, located at an intermediate point along the cause-effect chain between the inventory (emissions) and the final damage to the environment (endpoints).** By focusing on midpoints, emissions are converted into category indicators such as kg CO_2-equivalent, mol H^+-equivalent, or MJ deficit, providing a scientifically robust assessment while avoiding the higher uncertainties associated with endpoint damage modeling.

There are different steps for this section, which are Classification, Midpoint characterization, damage characterization (End point), Normalization and Weighting. This study use method EN 15804 which only considered first two steps stopping at Midpoint characterization and not continuing to aggregting the midpoint impact categories into damage categories such as damage to human health or ecosystem quality.

The results are presented at midpoint level in accordance with EF EN 15804, which ensures a balance between environmental relevance and methodological robustness, avoiding the additional uncertainties associated with endpoint damage modeling.

In this study the impact categories analyzed are **climate change**, specifically differentiated into **biogenic, fossil, and land-use-related contributions**, **ozone depletion**, **photochemical ozone formation**, **acidification**, and **eutrophication**, with distinctions made between **freshwater, marine, and terrestrial** impacts. In addition, the assessment considers **resource use** and **water use**.

The results are expressed per **functional unit (FU)** and reported according to life cycle modules in line with **EN 15804**:

- **A1–A3**: Product stage (raw material supply, transport, manufacturing)
- **B4**: Replacement of components
- **B6**: Operational energy use
- **C3**: Waste processing
- **C4**: Disposal
- **D**: Benefits beyond the system boundary (recycling potential)

The first parts are dedicated to total systems, which are Radiator system, Radiant Floor system and Fancoil system impact assessments and then based on the results some categories are analyzed in more detail.

2.2.4.1. Radiator System

Following tables present the Life Cycle Impact Assessment (LCIA) results of the radiator heating system, obtained using **SimaPro** software. The assessed system includes four steel radiators, One boiler, Distribution pipes and Manifold. These components were described in detail in the previous section.

The impact categories are expressed in their respective reference units (e.g., kg CO_2 eq, kg N eq, kg Sb eq), allowing environmental burdens to be quantified and compared across life cycle stages.

Table 37 shows in general results from Module A1-C4 in a column and separately Module D in another column representing environmental burdens and environmental credits from recycling.

From an environmental standpoint, the critical points are the categories with the highest relative contribution to the total impact. From the table below, we can see that Resource use, fossil has the highest absolute impact, then climate change fossil stands in the second highest impact as an indicator of climate change impact category. Also considering chemical impact categories, photochemical ozone formation is relatively high by contributing to smog formation, also water use based on the regional issues could be considered as a significant concern.

On the other hand, module D presents positive effect showing negative values across all categories. Among the data we can see high savings in between categories such as Acidification or Eutrophication, freshwater. In impact category Resource use, minerals and metals although the values seem low, however module D offsets roughly 74% of the upstream mineral resource use expressing excellent recovering of metals.

In contrast, three categories of Resource use, fossil, climate change fossil as results of burned fossil fuels and ozone depletion show lowest saving by module D. showing the impact is permanent and unavoidable.

Table 37: Total and module D LCIA results of radiator system

Impact category	Unit	Total (A1-C4)	Module D
Acidification	mol H+ eq/ FU	2.39E-04	-7.47E-05
Climate change	kg CO_2 eq /FU	3.02E-01	-4.45E-03
Climate change - Biogenic	kg CO_2 eq/ FU	1.16E-04	-1.23E-05
Climate change - Fossil	kg CO_2 eq/ FU	3.02E-01	-4.42E-03
Climate change - Land use and LU change	kg CO_2 eq/ FU	4.79E-05	-1.84E-05
Eutrophication, marine	kg N eq/ FU	6.03E-05	-6.28E-06
Eutrophication, freshwater	kg P eq/ FU	1.23E-05	-5.96E-06
Eutrophication, terrestrial	mol N eq/ FU	5.74E-04	-7.47E-05
Ozone depletion	kg CFC11 eq/ FU	7.12E-09	-3.49E-11
Photochemical ozone formation	kg NMVOC eq/ FU	5.56E-04	-2.35E-05
Resource use, fossils	MJ/ FU	4.32E+00	-4.98E-02
Resource use, minerals and metals	kg Sb eq/ FU	1.03E-06	-7.61E-07
Water use	m^3 depriv./ FU	7.24E-03	-1.62E-03

The next table represents a detailed breakdown for hotspot analysis. It is representing the contribution of each module to the total environmental burdens. At first view it is obvious that Module B6 is the dominant environmental hotspot across all other impact categories. As mentioned above the most significant impacts are climate change, fossil resource use, ozone depletion and photochemical ozone formation which more than 90% of the impacts are related to this module.

While B6 is the largest, two other module also has significant impact which are B4 related to replacement of components of the system and Module A1-3 related to manufactured materials production. Looking at

Module B4, module shows a good contribution to two impact categories, which are resource use, minerals and metals by contributing around 48% of total impact in this category and Eutrophication, fresh water which contributes around 41% of total impact.

Looking at the values of Module A1-3, almost the same categories play a role in this module like Module B4 with slightly different performance, showing 42% of total impact category of resource use, mineral and metals.

Modules C3 and C4 have environmental impacts that are several orders of magnitude smaller than other modules.

Table 38: LCIA results in all modules of radiator system

Impact category	Unit	Module A1-3	Module B6	Module B4	Module C3	Module C4	Total
Acidification	mol H+ eq/ FU	4.89E-05	1.28E-04	6.22E-05	3.39E-07	8.54E-09	2.39E-04
Climate change	kg CO_2 eq /FU	4.31E-03	2.91E-01	6.51E-03	2.13E-04	8.94E-06	3.02E-01
Climate change - Biogenic	kg CO_2 eq/ FU	7.50E-06	1.58E-05	6.12E-05	3.15E-05	2.49E-08	1.16E-04
Climate change - Fossil	kg CO_2 eq/ FU	4.29E-03	2.91E-01	6.43E-03	1.82E-04	8.91E-06	3.02E-01
Climate change - Land use and LU change	kg CO_2 eq/ FU	1.42E-05	1.71E-05	1.65E-05	5.12E-08	3.61E-10	4.79E-05
Eutrophication, marine	kg N eq/ FU	5.04E-06	4.80E-05	7.14E-06	1.09E-07	1.97E-08	6.03E-05
Eutrophication, freshwater	kg P eq/ FU	3.93E-06	3.23E-06	5.09E-06	1.95E-08	1.11E-10	1.23E-05
Eutrophication, terrestrial	mol N eq/ FU	5.72E-05	4.37E-04	7.94E-05	9.58E-07	3.75E-08	5.74E-04
Ozone depletion	kg CFC11 eq/ FU	4.90E-11	7.01E-09	6.10E-11	7.05E-13	4.21E-14	7.12E-09
Photochemical ozone formation	kg NMVOC eq/ FU	1.95E-05	5.10E-04	2.65E-05	2.98E-07	1.60E-08	5.56E-04
Resource use, fossils	MJ/ FU	5.41E-02	4.19E+00	7.30E-02	5.93E-04	3.07E-05	4.32E+00
Resource use, minerals and metals	kg Sb eq/ FU	4.33E-07	9.37E-08	4.99E-07	1.42E-09	3.15E-12	1.03E-06
Water use	m^3 depriv./ FU	1.38E-03	4.17E-03	1.69E-03	5.23E-06	-1.81E-07	7.24E-03

The Life Cycle Impact Assessment (LCIA) results of the radiator heating system, based on the functional unit of delivering **1 kWh of heat to the case study apartment**, highlight several key environmental insights across the assessed life cycle stages. The analysis shows that **resource use (fossils)** and **climate change (fossil)** represent the most significant environmental burdens, with total impacts of **4.32E+00 MJ / FU** and **3.02E-01 kg CO_2 eq / FU**, respectively, indicating the importance of energy consumption and fossil fuel dependency in the overall environmental profile of the system.

When examining the life cycle modules, **Module B6 (operational energy use)** clearly emerges as the dominant environmental hotspot, contributing to more than 90% of impacts in major categories such as climate change, fossil resource use, ozone depletion and photochemical ozone formation.

In addition to operational impacts, **Module B4 (component replacement)** and **Module A1–A3 (material production)** also play an important role, particularly in categories related to **mineral and metal resource use** (with 4.99E-07 kg Sb eq / FU in **B4** and 4.33E-07 in **A1–A3**) and freshwater eutrophication (with 5.09E-06 kg P eq / FU in **B4** and 3.93E-06 in **A1–A3**), reflecting the environmental relevance of material extraction and component replacement during the system's lifetime. Conversely, end-of-life processes **(Modules C3–C4)** contribute only marginally to the total impacts, with values typically several orders of magnitude lower than other modules.

2.2.4.2. Radiant Floor System

This part is related to results from impact assessment of radiant floor system and the tables below represent in detail. This system as mentioned in before chapters consists of radiant floor pipes, distribution pipes between manifold and boiler, manifold, boiler and towel dryer.

The table below presents general results from total modules impacting environmental burdens and Module D as credits to offset these impacts related to radiant floor system assessment. **Total (A1-C4)** represents the total environmental burden of the product system, covering all stages from raw material extraction (A1) to the end-of-life (C4). A positive value indicates a negative environmental impact.

Module D represents the **net benefits** (or loads) from recycling, reuse, and recovery beyond the system boundary. The **negative values** here are positive for the environment; they show the "credits" or avoided burdens from future recycling of materials.

Table 39: Total and module D LCIA results of radiant floor system

Impact category	Unit	Total (A1-C4)	Module D
Acidification	mol H+ eq/ FU	2.13E-04	-6.45E-05
Climate change	kg CO_2 eq /FU	2.82E-01	-2.49E-03
Climate change - Biogenic	kg CO_2 eq/ FU	2.15E-04	-1.13E-05
Climate change - Fossil	kg CO_2 eq/ FU	2.82E-01	-2.46E-03
Climate change - Land use and LU change	kg CO_2 eq/ FU	3.98E-05	-1.69E-05
Eutrophication, marine	kg N eq/ FU	5.34E-05	-4.34E-06
Eutrophication, freshwater	kg P eq/ FU	1.01E-05	-5.01E-06
Eutrophication, terrestrial	mol N eq/ FU	5.07E-04	-5.44E-05
Ozone depletion	kg CFC11 eq/ FU	6.70E-09	-2.56E-11
Photochemical ozone formation	kg NMVOC eq/ FU	5.13E-04	-1.67E-05
Resource use, fossils	MJ/ FU	4.04E+00	-2.98E-02
Resource use, minerals and metals	kg Sb eq/ FU	9.84E-07	-7.23E-07
Water use	m^3 depriv./ FU	7.57E-03	-1.23E-03

The data reveals that the system's environmental footprint is dominated by three main categories comparing orders of magnitude. The dominant hotspot is climate change specifically fossil indicator, representing heavy reliance on fossil fuel energy, second is resource use, fossil, which presents depletion of non-renewable energy resources, and the third category is water use, which measures the volume of water consumed, weighted by local water scarcity.

Regarding Module D, in three categories of Acidification, Resource use, minerals and metals and Eutrophication freshwater credits are respectively 30%, 73.5% and 50% of total impacts. However at the critical points mentioned such as climate change or resource use these credits are very small compared to the total impacts. For example, the Climate Change credit (-2.49E-03) is only about **0.88%** of the total impact (2.82E-01).

Table 40: LCIA results in all modules of radiant floor system

Impact category	Unit	Module A1-3	Module B4	Module B6	Module C3	Module C4	Total
Acidification	mol H+ eq/ FU	3.79E-05	4.59E-05	1.30E-04	1.84E-07	1.04E-08	2.13E-04
Climate change	kg CO_2 eq /FU	2.09E-03	2.77E-03	2.77E-01	1.84E-04	1.77E-05	2.82E-01
Climate change - Biogenic	kg CO_2 eq/ FU	-1.30E-06	2.60E-06	2.14E-04	-5.06E-08	1.78E-08	2.15E-04
Climate change - Fossil	kg CO_2 eq/ FU	2.09E-03	2.75E-03	2.77E-01	1.84E-04	1.77E-05	2.82E-01
Climate change - Land use and LU change	kg CO_2 eq/ FU	9.07E-06	1.41E-05	1.65E-05	2.56E-08	3.39E-10	3.98E-05
Eutrophication, marine	kg N eq/ FU	2.95E-06	3.78E-06	4.66E-05	4.53E-08	3.90E-08	5.34E-05
Eutrophication, freshwater	kg P eq/ FU	2.97E-06	3.59E-06	3.55E-06	9.13E-09	1.11E-10	1.01E-05
Eutrophication, terrestrial	mol N eq/ FU	3.57E-05	4.50E-05	4.26E-04	5.00E-07	4.70E-08	5.07E-04
Ozone depletion	kg CFC11 eq/ FU	3.55E-11	2.43E-11	6.64E-09	3.02E-13	5.26E-14	6.70E-09
Photochemical ozone formation	kg NMVOC eq/ FU	1.27E-05	1.45E-05	4.86E-04	1.47E-07	2.22E-08	5.13E-04
Resource use, fossils	MJ/ FU	3.41E-02	3.20E-02	3.98E+00	2.49E-04	3.71E-05	4.04E+00
Resource use, minerals and metals	kg Sb eq/ FU	4.07E-07	4.60E-07	1.17E-07	9.19E-10	3.44E-12	9.84E-07
Water use	m^3 depriv./ FU	1.01E-03	9.62E-04	5.59E-03	3.06E-06	-7.00E-07	7.57E-03

Table 40, presents the results in Modules for radiant floor system. by comparing data it is obvious that B6 same as radiator system is the dominant contributor to environmental impacts. Critical categories were discussed before such as climate change fossil and fossil resources use, which here it is observed that are driven by Module B6. While this module is the dominant contributor among other, Module B4 and Module A1-3 also contribute to emissions in two categories significantly. Module A1-3 and Module B4 account for respectively 41% and 47% of total in impact category Resource use, minerals and metals, and 29% and 35% of total in impact category Freshwater Eutrophication. The rest of modules which are C3 and C4 at this stage are environmentally negligible as their contribution seem less than 1% at most of the impact categories. A particular notice may go through climate change biogenic indicator which has a negative value expressing temporal carbon storage at this system.

2.2.4.3. Fancoil System

The last analyzed system is Fancoil system, which consists of three fancoils, towel dryer, distribution pipes, manifold and boiler. The presented results in each category is based on functional unit of 1 kWh delivered heating energy to the study case apartment. Two columns as other system analysis show total impact through whole life cycle and Module D as benefits from beyond the system boundary.

In the order of magnitude some of the impact categories could be recognized critical. Same as other systems effected by fossil fuel usage such as natural gas or electricity usage, impact categories of Fossil Resource Use, Climate change-fossil has higher values. The other concern may also be related to Water Use, even though the number is small, water scarcity is a high-priority impact category in environmental regulations.

Regarding Module D, all the negative values show a positive impact environmentally in each category. As this module accounts benefits from recycling or recovering energy, at some impact categories environmental burdens could be covered significantly by this module, which are Resource use, minerals and metals covering 71% of total impact categories, Eutrophication-freshwater covering 48% and Acidification covering almost 31% of total impact at that categories. Other categories effect of module d values seem lower than these percentages.

Table 41: Total and module D LCIA results of Fancoil system

Impact category	Unit	Total (A1-C4)	Module D
Acidification	mol H+ eq/ FU	2.63E-04	-8.30E-05
Climate change	kg CO_2 eq /FU	2.98E-01	-3.80E-03
Climate change - Biogenic	kg CO_2 eq/ FU	6.01E-04	-2.14E-05
Climate change - Fossil	kg CO_2 eq/ FU	2.98E-01	-3.75E-03
Climate change - Land use and LU change	kg CO_2 eq/ FU	5.26E-05	-2.29E-05
Eutrophication, marine	kg N eq/ FU	6.07E-05	-5.98E-06
Eutrophication, freshwater	kg P eq/ FU	1.34E-05	-6.46E-06
Eutrophication, terrestrial	mol N eq/ FU	5.86E-04	-7.36E-05
Ozone depletion	kg CFC11 eq/ FU	7.03E-09	-3.92E-11
Photochemical ozone formation	kg NMVOC eq/ FU	5.53E-04	-2.30E-05
Resource use, fossils	MJ/ FU	4.27E+00	-4.50E-02
Resource use, minerals and metals	kg Sb eq/ FU	1.26E-06	-8.99E-07
Water use	m^3 depriv./ FU	1.15E-02	-1.69E-03

Next table presents values of total impact in each Modules from A1-3 to C4. Based on what discussed before Module B6 is the dominator among other modules impacting the total values. However in one indicator which is Resource use-minerals and metals the situation is different. B4 in this category has highest value than others expressing the replacement of components effect at this category and then second highest value is related to Module A1-3.

Moreover, the same scenario has happened like radiators and radiant floor, Module B4 has the highest values in impact categories after B6 and Module A1-3 is placed as third highest contributor. Two impact categories as mentioned above are highly effected by these modules, which are Resource use-minerals and metals and Eutrophication-freshwater which almost 86% and 65% of total impacts are related to these modules respectively.

Table 42: LCIA results in all modules of Fancoil system

Impact category	Unit	Module A1-3	Module B4	Module B6	Module C3	Module C4	Total
Acidification	mol H+ eq/ FU	4.86E-05	6.27E-05	1.52E-04	3.23E-07	6.35E-09	2.63E-04
Climate change	kg CO_2 eq /FU	3.01E-03	4.74E-03	2.90E-01	2.82E-04	6.97E-06	2.98E-01
Climate change - Biogenic	kg CO_2 eq/ FU	4.25E-06	3.78E-06	5.93E-04	-9.85E-08	2.01E-08	6.01E-04
Climate change - Fossil	kg CO_2 eq/ FU	2.99E-03	4.71E-03	2.90E-01	2.82E-04	6.95E-06	2.98E-01
Climate change - Land use and LU change	kg CO_2 eq/ FU	1.51E-05	1.95E-05	1.79E-05	4.56E-08	2.55E-10	5.26E-05
Eutrophication, marine	kg N eq/ FU	4.10E-06	5.74E-06	5.08E-05	7.81E-08	1.54E-08	6.07E-05
Eutrophication, freshwater	kg P eq/ FU	3.80E-06	4.93E-06	4.62E-06	1.63E-08	8.38E-11	1.34E-05
Eutrophication, terrestrial	mol N eq/ FU	4.85E-05	6.69E-05	4.69E-04	8.64E-07	2.80E-08	5.86E-04
Ozone depletion	kg CFC11 eq/ FU	3.48E-11	4.16E-11	6.95E-09	5.29E-13	3.17E-14	7.03E-09
Photochemical ozone formation	kg NMVOC eq/ FU	1.63E-05	2.21E-05	5.14E-04	2.56E-07	1.20E-08	5.53E-04
Resource use, fossils	MJ/ FU	4.07E-02	5.48E-02	4.17E+00	4.40E-04	2.29E-05	4.27E+00
Resource use, minerals and metals	kg Sb eq/ FU	4.89E-07	5.91E-07	1.75E-07	1.64E-09	2.42E-12	1.26E-06
Water use	m^3 depriv./ FU	1.17E-03	1.44E-03	8.90E-03	5.38E-06	-2.09E-07	1.15E-02

The life cycle impact assessment has provided a clear understanding of the environmental profiles for the three heating systems designed to deliver 1 kWh of heating energy. The analysis reveals that the environmental performance of all systems is predominantly driven by operational energy consumption

(Module B6), specifically the use of natural gas and electricity. This is most evident in the **Climate change – Fossil** and **Resource use, fossils** categories, which register the highest magnitude of impact across all systems. The total impacts in these categories are so significant that they overshadow contributions from other life cycle stages, establishing energy consumption as the primary environmental hotspot for all three systems. Water use also emerges as a consistently notable impact category with relatively high values across the board.

A distinct contrast is observed when examining other impact categories. While energy-related impacts dominate, **Eutrophication, freshwater** and **Resource use, minerals and metals** are governed by a different life cycle dynamic. These two categories are overwhelmingly shaped by the production and manufacturing stages (Modules A1-A3) and the replacement of components (Module B4). This trend is consistent across all three systems. Furthermore, the end-of-life benefits and credits (Module D) are most pronounced for these same two categories, indicating that the materials used in the systems hold significant potential for recovery and recycling, thereby offsetting some of their initial burdens.

While the general trends among the systems look the same, the table below shows a comparison between the systems in terms of specific impact categories. In the energy-dominated categories, the **Radiator System** exhibits the highest impact for **Climate change – Fossil and Resource use-fossil**. This can be directly attributed to its requirement for the highest flow temperature, which results in the lowest boiler efficiency among the three configurations. Conversely, the **Radiant Floor System** consistently shows the lowest impact among system configurations, benefiting from its low-temperature requirement and thus the highest boiler efficiency.

For the remaining categories—**Eutrophication, freshwater**; **Resource use, minerals and metals**; a different hierarchy is observed. The **Radiant floor System** presents the lowest total impacts, while the **Fancoil System** consistently records the highest. The **Radiator System** sits in between. This suggests that the variation in materials of system configurations, and the relative metal intensity of these configurations during production and replacement phases, leads to disparate outcomes in these impact categories. The configuration with the highest material intensity is fancoils, while the configuration with the lowest metal intensity is radiant floor, utilising materials with a longer life span.

The situation is different in the **water use** impact category. In this case, the radiant floor system has a slightly higher impact than the radiator system, and the fan coil system has the highest impact of all the systems examined. The difference in impact between the radiant floor system and radiator system may be related to the number of components or materials used in their construction.

The following section will delve deeper into these key impact categories, exploring the contributions from specific materials, components, and operational phases to fully explain the differences observed between the three heating systems.

Table 43: Total LCIA results of all systems in specific impact categories

Systems\ Impact categories	Climate change - Fossil	Resource use, fossils	Eutrophication, freshwater	Resource use, minerals and metals	Water use
	kg CO_2 eq/ FU	MJ/ FU	kg P eq/ FU	kg Sb eq/ FU	m^3 depriv./ FU
Radiator System					
Total (A1-C4)	3.02E-01	4.32E+00	1.23E-05	1.03E-06	7.24E-03
Module D	-4.42E-03	-4.98E-02	-5.96E-06	-7.61E-07	-1.62E-03
Radiant Floor System					
Total (A1-C4)	2.82E-01	4.04E+00	1.01E-05	9.84E-07	7.57E-03
Module D	-2.46E-03	-2.98E-02	-5.01E-06	-7.23E-07	-1.23E-03
Fancoil System					
Total (A1-C4)	2.98E-01	4.27E+00	1.34E-05	1.26E-06	1.15E-02
Module D	-3.75E-03	-4.50E-02	-6.46E-06	-8.99E-07	-1.69E-03

Following this overarching comparison, a closer examination of the contribution analysis for each heating system makes it unequivocally clear where analytical focus must be directed. The dominance of operational energy consumption is not merely a qualitative observation but is quantitatively confirmed by the proportional contribution of Module B6 to the total life cycle impacts. In the **Climate change – Fossil** category, Module B6 accounts for an overwhelming 96.39% of the total impact for the Radiator System, 98.21% for the Radiant Floor System, and 97.32% for the Fancoil System. This pattern is even more pronounced in the **Resource use, fossils** category, where Module B6 constitutes 97.05%, 98.36%, and 97.75% of the total impacts for the Radiator, Radiant Floor, and Fancoil systems, respectively. These percentages unequivocally identify the operational phase—specifically the combustion of natural gas for heating and the consumption of electricity for auxiliary components—as the singular most critical life cycle stage driving these two impact categories. Any meaningful strategy to reduce the carbon footprint or fossil resource depletion associated with these heating systems must therefore address the efficiency and energy source of Module B6.

Conversely, a distinctly different allocation of impacts is observed for the remaining categories. In the cases of **Eutrophication, freshwater** and **Resource use, minerals and metals**, the contribution from Module B6 diminishes significantly. Instead, the impact burdens are distributed across other life cycle stages, with the product and material production stages (Modules A1-A3) and the replacement of components (Module B4) emerging as the primary contributors in all three systems. Therefore, the subsequent analysis will first conduct a deep dive into **Module B6**, examining its role across all four impact categories to fully understand the drivers behind the energy-related impacts. Following this, the focus will shift specifically to **Modules A1-A3 and B4**, concentrating exclusively on the two impact categories they dominate: **Eutrophication-freshwater** and **Resource use - minerals and metals**. This dual-pronged approach will ensure a comprehensive and targeted investigation of the most significant environmental hotspots identified in the life cycle of each heating system.

2.2.4.4. *Climate Change-fossil*

The "Climate Change – Fossil" impact category quantifies a product system's contribution to the enhanced greenhouse effect resulting specifically from fossil-based emissions. This includes greenhouse gases (GHGs) released from the combustion of coal, oil, and natural gas, as well as from fossil-based industrial processes like cement and plastic production. It is distinct from biogenic CO_2 emissions, which originate from biomass and are part of the natural carbon cycle.

The underlying mechanism is the greenhouse effect, where certain gases in the atmosphere absorb infrared radiation that would otherwise escape to space, thereby trapping heat and warming the Earth's surface. Anthropogenic activities have significantly increased atmospheric concentrations of these gases, driving modern climate change characterized by rising temperatures and extreme weather.

To compare the impact of different emissions, the Global Warming Potential (GWP) concept is used. GWP is a metric that compares the radiative efficiency and atmospheric lifetime of a gas to that of carbon dioxide (CO_2) over a specific timeframe, typically 100 years. It answers the question: "How much energy will one kilogram of this gas absorb over 100 years, compared to one kilogram of CO_2?"

In practice, each fossil-based emission is multiplied by its specific GWP characterization factor. The results are aggregated into a single score expressed in kilograms of CO_2 equivalent (kg CO_2-eq). For example, fossil methane (CH_4) is approximately 30 times more potent than CO_2, while nitrous oxide (N_2O) is nearly 273 times more potent. The total score, in kg CO_2-eq, represents the product's potential contribution to climate change, with a lower score indicating a lower impact.

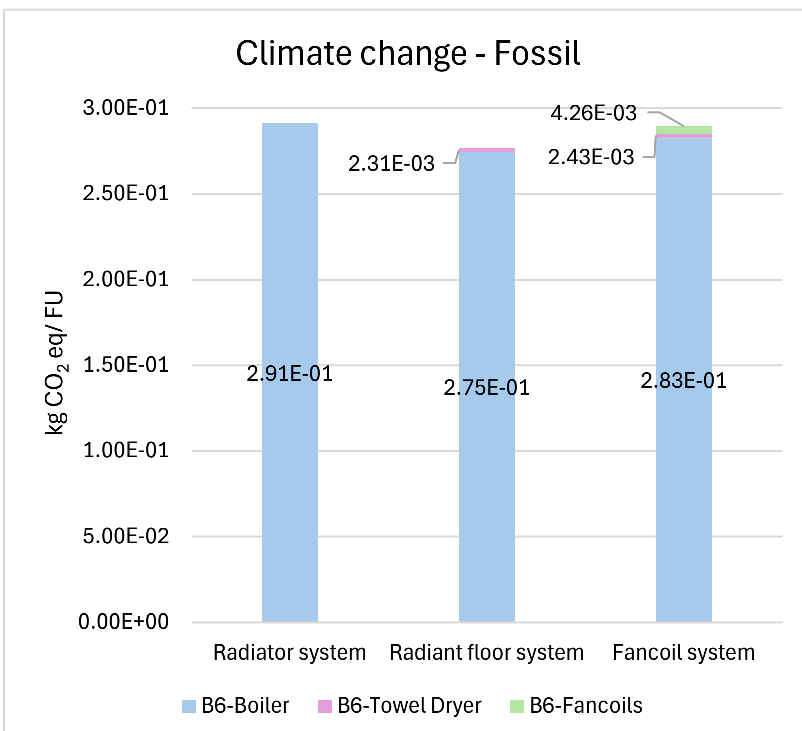

Figure 42: Module B6 LCIA results of all systems in climate change-fossil category

Figure 42 presents the contribution analysis for the "Climate Change – Fossil" impact category, expressed in kilograms of CO_2 equivalent per functional unit (kg CO_2 eq./FU). The chart compares the performance of three different heating system configurations (Radiator, Radiant Floor, and Fan Coil) by breaking down the total climate impact into the contributions from three specific life cycle modules: the boiler (B6-Boiler), the towel dryer (B6-Towel Dryer), and the fancoils (B6-Fancoils). This level of disaggregation is crucial for identifying the primary sources of greenhouse gas emissions within each system.

The analysis reveals that while the total emissions across the three configurations are numerically close, the **Radiator system** emerges as the **least efficient** option from a climate perspective.

The **Radiator system** exhibits the highest total impact, reaching approximately **2.91E-01 kg CO_2 eq./FU**. This impact is overwhelmingly dominated by the **B6-Boiler** module. Because radiators require significantly higher operating temperatures to provide adequate heat, the boiler operates at its lowest efficiency in this configuration, resulting in the highest emission intensity among the three studied systems.

The **Fan Coil system** shows a slightly lower overall impact compared to the radiator setup, totaling roughly **2.90E-01 kg CO_2 eq./FU**. In this configuration, the **B6-Boiler** remains the primary source of emissions **(2.83E-01 kg CO_2 eq./FU)**. Auxiliary components, including the **towel dryer (2.43E-03 kg CO_2 eq./FU)** and **fan coils (4.26E-03 kg CO_2 eq./FU)**, contribute the remainder. The slight difference in towel dryer emissions between this and the Radiant Floor system stems from differences in the functional unit, despite identical usage patterns.

The **Radiant Floor system** achieves the **lowest total impact** at approximately **2.77E-01 kg CO_2 eq./FU**. While the **B6-Boiler** is still the dominant contributor (**2.75E-01 kg CO_2 eq./FU**), its emissions are noticeably reduced. This confirms that radiant floor technology allows the boiler to operate at lower temperatures and much higher efficiencies, thereby minimizing the system's carbon footprint.

From a climate change perspective, the **Radiant Floor system** is the preferable option, exhibiting **the lowest potentia**l for global warming. Conversely, the Radiator system is the least desirable due to its higher operational temperature requirements and subsequent drop in boiler efficiency. This analysis underscores how the synergy between terminal units (like floors vs. radiators) and the main heat source profoundly influences the overall environmental performance of a building's heating system.

2.2.4.5. Resource Use-fossil

Resource use – fossil is an impact category that addresses the consumption of non-renewable fossil resources, such as crude oil, natural gas, and coal. It focuses on the depletion of these finite geological stocks, which are consumed far faster than they can be regenerated. The category measures the potential consequences of extracting these resources, quantifying the "scarcity" or "deprivation" created for future generations by using them today. Fundamentally, it seeks to answer the question: how much less of this resource will be available in the future because of its use now?

To calculate this impact, the method uses characterization factors based on the ratio of a resource's annual production to its remaining global reserves. A higher production-to-reserves ratio indicates a scarcer resource, such as oil, and results in a higher characterization factor compared to a more abundant one like coal. The final indicator score is typically expressed in units such as MJ deficit or kg oil equivalent. This category is particularly important because it addresses the ethical dimension of intergenerational equity, ensuring that future generations have access to resources. It also provides a key metric for comparing the resource efficiency of different products or technologies, ensuring that a comprehensive sustainability assessment goes beyond just climate change to include the long-term availability of natural capital.

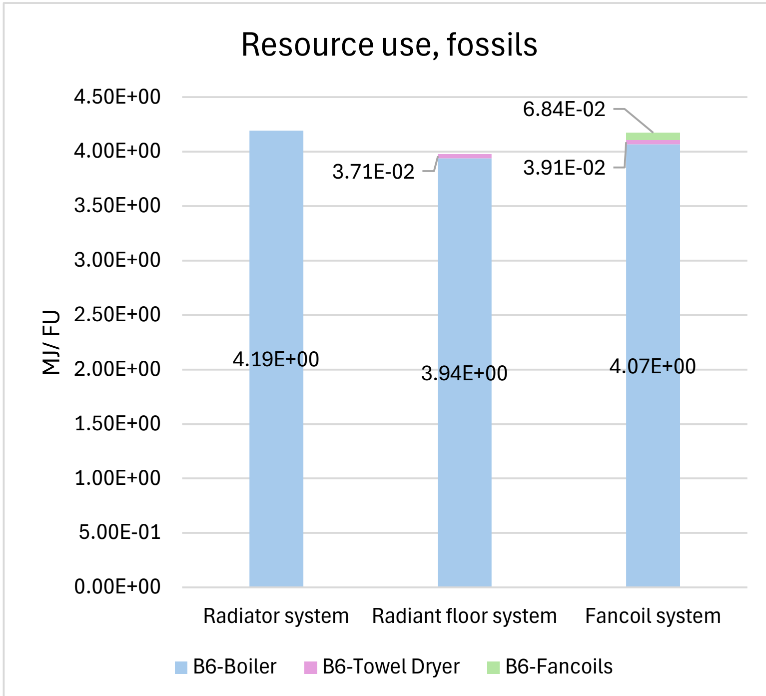

Figure 43: Module B6 LCIA results of all systems in Resource use-fossil category

Figure 43 presents the results for the **resource use, fossils** impact category, expressed in **MJ per functional unit (MJ/FU)**, for the three heating system configurations. This indicator represents the total amount of fossil energy resources consumed during the assessed life-cycle.

From an environmental perspective, the **Radiator system** presents **the highest fossil resource consumption** with a total value of **4.19 MJ/FU**. The **Fan Coil system** follows closely with **4.17 MJ/FU**, while the **Radiant Floor system** shows the **lowest consumption** at approximately **3.98 MJ/FU**. This hierarchy indicates that the radiant floor configuration performs significantly better than the other heating systems, whereas the radiator configuration results in the highest overall resource demand.

When analyzing the contribution of the **boiler (Module B6)**, the impact of operational efficiency becomes clear. The **Radiator system** exhibits the highest boiler energy demand (**4.19 MJ/FU**) because it must operate at higher supply temperatures, which reduces the heat generation system's efficiency. In contrast, the **Radiant Floor system** shows the lowest value (**3.94 MJ/FU**), reflecting its ability to provide comfort at lower temperatures. The **Fan Coil system** falls between the two at **4.07 MJ/FU**.

In addition to the boiler, **electricity use from auxiliary components** influences the total fossil resource demand:

Electric Towel Dryers: These contribute **3.71E-02 MJ/FU** in the **radiant floor system** and **3.91E-02 MJ/FU** in the **fan coil system**. The higher value in the fan coil system is due to **functional unit normalization** rather than a difference in actual usage.

Fan Coil Units: The fan coil system includes an additional demand of approximately **6.84E-02 MJ/FU** for **fan operation**.

While these electrical loads are small compared to the boiler, they explain why the Fan Coil system's total consumption (4.17 MJ/FU) is higher than the Radiant Floor system, even though the fan coil's auxiliary units are more efficient than traditional radiators.

The results highlight that the **Radiator system** is the least efficient option due to its high boiler energy demand. While the fan coil system has the added burden of electricity for fans, the radiator system's poor boiler efficiency at high temperatures remains the dominant factor in its high environmental impact. These findings emphasize that choosing low-temperature distribution systems, like **radiant floors**, is the most effective way to reduce fossil resource dependency.

2.2.4.6. Resource Use- minerals and metals

The impact category **Resource use – minerals and metals** evaluates the potential depletion of non-renewable mineral and metal resources caused by the extraction of raw materials required throughout the life cycle of a product or system. This category focuses on **abiotic resources**, meaning natural resources that do not regenerate on human time scales, such as metals (e.g., copper, aluminum, iron) and mineral materials used in industrial production and construction.

In Life Cycle Impact Assessment (LCIA), this category quantifies how the consumption of these resources contributes to the **long-term reduction of available reserves in the Earth's crust**. Since mineral and metal deposits are finite, their continuous extraction may lead to increasing scarcity, requiring future generations to exploit lower-grade ores, deeper deposits, or more energy-intensive extraction processes. Therefore, this impact category represents the potential pressure that current resource use places on the availability of these materials in the future.

The indicator used to quantify this impact is based on the **Abiotic Depletion Potential (ADP)**. This metric considers both the **rate at which a resource is extracted** and the **total amount of that resource available in the Earth's reserves**. Resources that are extracted rapidly relative to their remaining reserves are considered more critical because their depletion risk is higher. In order to make results comparable across different materials, the impacts are normalized relative to a reference element, commonly **antimony (Sb)**.

For this reason, the results of this impact category are expressed in the unit **kilograms of antimony equivalents (kg Sb-eq)**. This unit represents the relative contribution of a material's extraction to resource depletion compared with antimony, which acts as the reference substance.

Assessing the use of mineral and metal resources is particularly important in sectors that rely heavily on raw materials, such as construction, electronics, and energy technologies. In building systems, for example, components like pipes, heat exchangers, radiators, and mechanical equipment contain large amounts of metals such as steel, copper, and aluminum. Evaluating this impact category helps identify which materials or system configurations require larger quantities of scarce resources and therefore contribute more significantly to resource depletion.

Considering resource use alongside other environmental indicators allows life cycle assessment to support more sustainable design decisions. By identifying systems that require fewer critical raw materials or enable higher recycling potential, it becomes possible to reduce long-term pressure on mineral reserves and move toward more resource-efficient technologies.

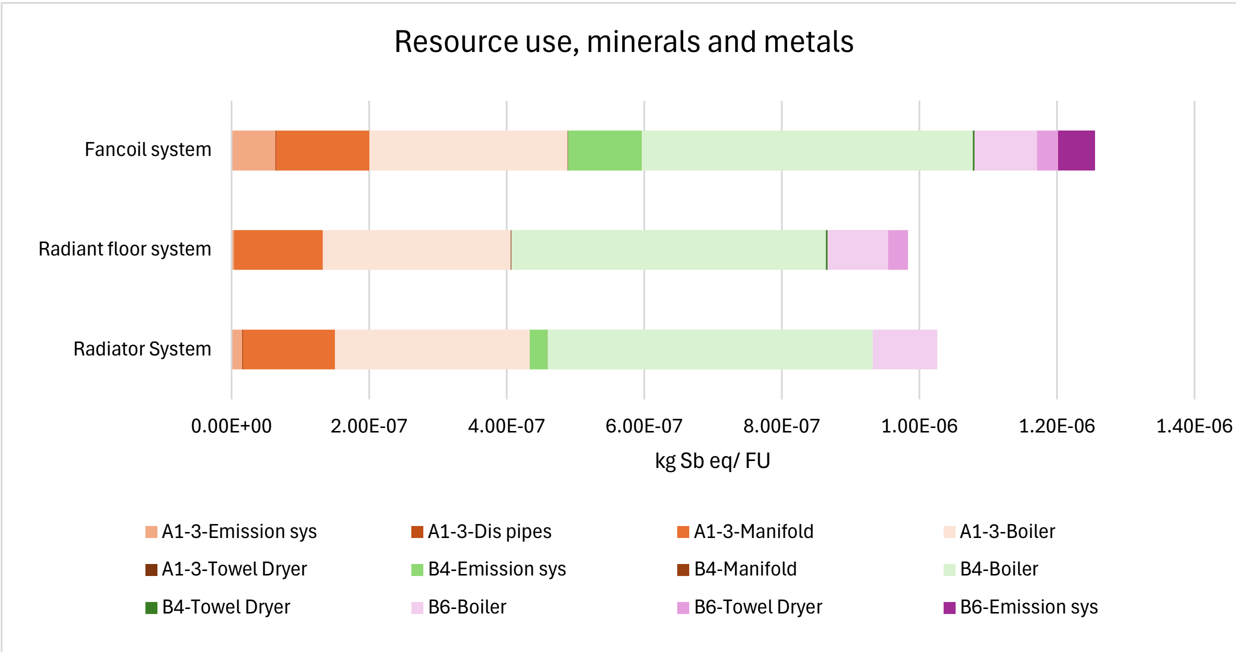

Figure 44: LCIA results of all systems in Resource use-minerals and metals

Figure 44 illustrates the impact results for **Resource use – minerals and metals** across the three studied heating systems: radiator, radiant floor, and fan-coil. Results are quantified in **kg Sb eq.** per functional unit, representing the abiotic depletion potential of mineral and metal resources throughout the systems' life cycles. The analysis focuses on modules **A1–A3 (product stage)**, **B4 (replacement stage)**, and **B6 (operational use stage)**, as these represent the primary contributors to this category.

From a life-cycle perspective, the **radiant floor system** achieves the lowest environmental impact. Conversely, the **fan-coil system** exhibits the highest impact, followed by the **radiator system**. These variations are driven by the specific material inventories of their respective components, including boilers, emission units, distribution networks, manifolds, and towel dryers.

The **gas boiler** emerges as the dominant contributor across all systems, primarily within **module B4**. This impact is attributed to the scheduled replacement of the unit at the end of its service life, necessitating a high consumption of metals such as **steel, aluminum, and copper**. The second-highest impact for this component occurs in **modules A1–A3**, where the extraction and processing of these metals—characterized by high abiotic depletion factors—drive the results. Notably, the impact of the boiler in **module B6** is marginal, a trend that remains consistent across all three configurations.

A consistent trend across all systems is observed for the **manifold**, where the impact in **modules A1–A3** significantly outweighs that of **module B4**. This is directly linked to the material inventory and maintenance assumptions: while the manifold's steel and plastic components are slated for replacement during its service life, the **brass body** is excluded from replacement due to its high durability and long lifespan. Consequently, the high impact in the product stage (**A1–A3**) is driven by the extraction and processing of brass (primarily copper and zinc), which possess high characterization factors for mineral depletion. The comparatively lower impact in **module B4** confirms that only minor steel and plastic parts are replaced, leaving the resource-intensive brass components in situ for the duration of the building's reference period.

Across all configurations, the impact of distribution pipes is negligible. This is due to their polymer-based composition and a service life that aligns with the building's reference period, thereby eliminating the need for replacement (**module B4**).

The differentiation between the three systems is largely dictated by the **emission units** and the presence of **towel dryers**:

- **Towel Dryers:** In radiant floor and fan-coil systems, towel dryers exhibit a minor contribution, primarily localized in **module B6**, with negligible impacts in other life-cycle stages.
- **Emission Units:** The heat emission elements show distinct profiles. **Radiant floor pipes** yield negligible impacts due to their polymer-based structure and low metallic content. **Radiators** demonstrate a moderate impact, while **fan-coil units** present the highest contribution in this category. This is likely due to their mechanical complexity and the higher density of metallic components compared to passive emitters.

Overall, these results underscore that **material intensity** and **component complexity** are the primary determinants of mineral and metal resource depletion. Metallic components—specifically boilers, manifolds, and fan-coil units—remain the critical "hotspots" driving the life-cycle impact of residential heating systems.

2.2.4.7. Eutrophication-Freshwater

The impact category **Eutrophication – Freshwater** evaluates the potential environmental damage caused by the release of nutrients into freshwater ecosystems such as rivers, lakes, and reservoirs. In Life Cycle Assessment (LCA), this category focuses mainly on emissions of **nutrient substances**, particularly **phosphorus compounds**, that can stimulate excessive biological growth in aquatic environments. These nutrient inputs may originate from industrial activities, wastewater discharges, agricultural runoff, or emissions associated with the production and use of materials throughout a product's life cycle.

Eutrophication occurs when an increased concentration of nutrients in water bodies promotes the rapid growth of **algae and aquatic plants**. Although nutrients are naturally present in ecosystems, excessive inputs disturb the natural balance of aquatic environments. The intense growth of algae can form dense blooms on the water surface, reducing light penetration and affecting submerged vegetation. As these organisms die and decompose, microorganisms consume large amounts of dissolved oxygen, which may lead to **oxygen depletion (anaerobic conditions)** in the water. This process can severely impact aquatic life and may result in the loss of fish, plants, and other organisms that depend on oxygen-rich environments.

Within LCIA, the freshwater eutrophication indicator quantifies the **potential contribution of nutrient emissions to this ecological imbalance**. Different nutrient substances have different capacities to cause eutrophication; therefore, characterization models convert their contributions into a common reference substance. For freshwater eutrophication, the indicator is typically expressed in **kilograms of phosphorus equivalents (kg P-eq)**. This unit reflects the relative potential of different emissions to contribute to nutrient enrichment in freshwater systems, with phosphorus being considered the limiting nutrient that most strongly drives eutrophication processes in many freshwater environments.

Assessing freshwater eutrophication is important because nutrient pollution represents a significant environmental challenge for water quality and ecosystem health. Excessive nutrient inputs can degrade aquatic ecosystems, reduce biodiversity, and affect water resources used for drinking water, recreation, and fisheries. In life cycle studies of products or systems, this impact category helps identify processes or materials that are associated with higher nutrient emissions to water bodies, allowing decision-makers to design solutions that minimize nutrient releases and reduce pressure on freshwater ecosystems.

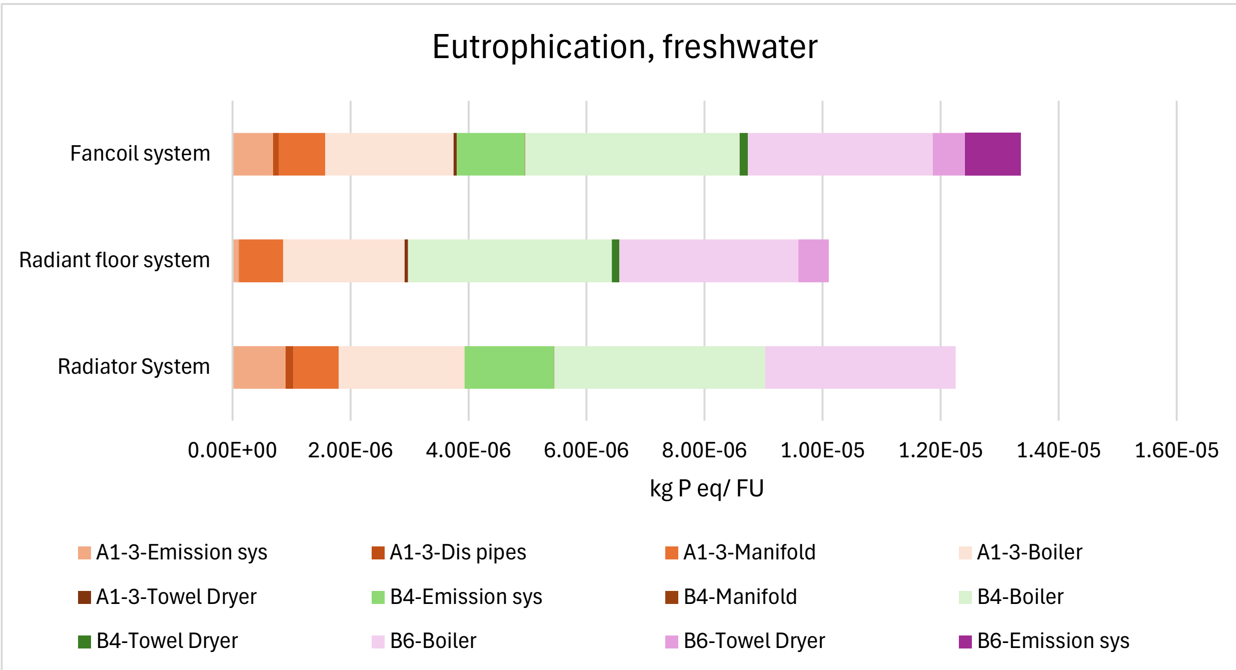

Figure 45: LCIA results of all systems in Eutrophication-freshwater

Figure 45 presents the **freshwater eutrophication** potential for the three heating configurations: radiator, radiant floor, and fan-coil systems. Similar to the resource depletion analysis, the results are disaggregated by modules **A1–A3 (product stage)**, **B4 (replacement stage)**, and **B6 (operational use stage)**. The overall trend mirrors the previous category, with the **radiant floor system** demonstrating the lowest overall impact, while the **fan-coil system** exhibits the highest, followed by the **radiator system**.

The **gas boiler** remains the primary contributor across all three configurations. The most significant impacts originate from **module B4 (replacement)**, followed by **module B6 (operational use)** and **modules A1–A3 (production)**. This distribution highlights two distinct environmental pressures:

1. The **material intensity** of the boiler, where the replacement of metallic components necessitates further resource extraction and manufacturing.
2. The **operational phase**, where the combustion of fossil fuels and the associated upstream energy chain generate nutrient-related emissions that contribute to freshwater eutrophication.

Consistent with the resource depletion category, the manifold shows a visible influence primarily in **modules A1–A3**. This is attributed to the extraction and processing of **brass**, which involves nutrient-releasing emissions during the mining phase. As established in the inventory, the impact in **module B4** remains low because only steel and plastic parts are replaced, while the brass body—the primary driver of eutrophication potential for this component—is retained.

The contribution of distribution pipes is negligible across all systems. A marginal impact is noted in the fan-coil and radiator systems; however, the radiant floor system shows almost no visible impact in **A1–A3** due to the reduced quantity of piping required for that specific configuration.

For radiant floor and fan-coil systems, the impact of towel dryers is almost exclusively localized in **module B6**. This is driven by the electricity consumed during operation, whereas the material-related impacts (A1–A3 and B4) remain minimal.

A notable shift in trends occurs when focusing on the heat emission elements (radiators, radiant floor pipes, and fan-coil units). Unlike the resource depletion category, **radiators** exhibit a relatively higher contribution here than other emission components.

While **fan-coil units** are more mechanically complex, their use of copper and aluminum results in a moderate impact in this category. In contrast, the high **steel content** of radiators drives a more significant eutrophication impact, as the production of steel typically involves higher nutrient releases (e.g., phosphate emissions to water during mining and coking). **Radiant floor pipes**, composed primarily of polymers, continue to show a negligible impact.

These results emphasize that freshwater eutrophication is highly sensitive to both the **frequency of component replacement** during the building's reference period and the **specific material choices** particularly the high steel content in radiators and the brass used in manifolds.

2.2.5. Interpretation

Following the guidelines of ISO 14044, this section aims to evaluate the results of the Life Cycle Impact Assessment (LCIA), draw conclusions, explain limitations, and make recommendations. Specifically, this analysis will:

- Identify the critical lifecycle stages (hotspots) for each heating system.
- Compare the three scenarios: Radiator System, Radiant Floor System, and Fancoil System.
- Verify the consistency and robustness of the results using a ratio check (kg CO_2 eq / MJ of Non-renewable primary energy).

2.2.5.1. Identification of environmental hotspots

The interpretation of the life cycle impact assessment (LCIA) results reveals that, across all three heating configurations analyzed in this study (radiator, radiant floor, and fan-coil systems), the most significant environmental impacts occur in impact categories related to fossil energy use. In particular, the impact categories **Climate Change – Fossil** and **Resource Use – Fossils** consistently show the highest contributions among all categories when providing the defined functional unit of **1 kWh of heating energy to the case study apartment**.

The results indicate that the dominant contributor to these impacts is **Module B6**, which represents the operational energy use during the use phase of the system. In all three systems, Module B6 is mainly associated with the **natural gas consumption of the boiler**, which provides the primary heat generation. Additionally, in the fan-coil and Radiant floor systems, the **electricity consumption of auxiliary components**, such as fan-coil units and towel dryers, contributes to the operational impacts due to the use of grid electricity. As a result, Module B6 overwhelmingly dominates energy-related impact categories across all analyzed systems.

Beyond the operational phase, the modules **A1–A3** and **B4** represent the second most significant contributors in several impact categories. Module **A1–A3** corresponds to the extraction and processing of raw materials of system components, while **Module B4** accounts for the replacement of components during the reference study period. These modules are therefore primarily associated with the **material composition of the heating systems**.

The influence of these modules becomes particularly visible in impact categories related to **Resource Use – Minerals and Metals** and **Eutrophication – Freshwater**, where relatively high contributions from A1–A3 and B4 are observed across all three systems. These impacts are largely driven by the production and replacement of metallic materials used in system components. Based on the life cycle inventory data, the main materials involved include **steel, aluminum, copper, brass, and polymer-based materials**.

The results show that components containing **metallic materials** generally contribute more significantly to these impact categories than polymer-based components. For example, polymer materials used in distribution pipes exhibit relatively low environmental impacts compared with metallic components within the systems. In contrast, components containing high amounts of metals tend to have a more substantial contribution to material-related impact categories.

One notable example is the **manifold component**, which contains **brass**, a material associated with relatively high environmental burdens in mineral resource use and eutrophication indicators. Similarly,

steel-based components, such as radiators, show noticeable contributions to eutrophication-related impacts compared with other system elements such as plastic pipes.

Certain components, including **boilers and fan-coil units**, are characterized by complex material compositions consisting of multiple metals and polymers. Due to their structural complexity and material intensity, these components contribute significantly across several impact categories. In particular, the **boiler** represents a key contributor not only in the operational phase (Module B6) but also in material-related categories due to the metals required for its manufacturing.

In contrast, the **end-of-life modules (C3 and C4)** show relatively minor contributions to the overall environmental profile of the heating systems. These modules represent processes related to waste sorting, incineration, and landfill at the end of the product life cycle. Across nearly all impact categories and system configurations, their contribution remains significantly lower compared with other life cycle stages.

Finally, **Module D**, which represents potential environmental benefits from recycling, reuse, and energy recovery, provides noticeable credits in certain material-related impact categories. In particular, categories such as **Resource Use – Minerals and Metals**, **Eutrophication – Freshwater**, and **Acidification** show a measurable reduction in total impacts due to the recovery of recyclable materials at the end of the system life cycle. In contrast, Module D has only a limited influence on categories primarily related to fossil energy use, where operational energy consumption remains the dominant factor.

Overall, the hotspot analysis highlights that **operational energy consumption during the use phase (Module B6)** represents the most critical environmental hotspot for all heating systems. At the same time, **material production and replacement (Modules A1–A3 and B4)** play an important role in material-related impact categories, particularly those associated with mineral resource depletion and aquatic eutrophication.

2.2.5.2. Comparison between heating systems

The comparison of the three heating configurations analyzed in this study — **radiator, radiant floor, and fan-coil systems** — demonstrates that the environmental performance of each system varies depending on the impact category considered. This observation indicates that it is not possible to identify a single heating system that performs best across all environmental indicators. Instead, each configuration shows advantages and disadvantages depending on the dominant processes and materials contributing to the respective impact categories.

As discussed in the hotspot analysis, the most significant impact categories for all systems are **Climate Change – Fossil** and **Resource Use – Fossils**, which are primarily driven by operational energy consumption during the use phase (Module B6). When comparing the systems in the **Climate Change – Fossil** category, the **radiant floor system shows the lowest environmental impact**, indicating the best performance among the three configurations for the defined functional unit of **1 kWh of heating energy delivered to the apartment**. In contrast, the **radiator system exhibits the highest impact**, while the **fancoil system shows intermediate performance**.

To understand these differences, it is important to consider the configuration and operation of each heating system. In all systems, the main heat generation component is the **boiler**, which operates using natural gas. However, additional components influence the overall operational energy consumption. For instance, in the radiant floor system analyzed in this case study, a **towel dryer is used for clothes drying**, which introduces additional electricity consumption during the use phase. As a result, the dominant Module B6 contribution in the radiant floor configuration consists of **natural gas consumption by the boiler together with electricity consumption by the towel dryer**.

Despite the presence of electricity consumption in systems other than the radiator configuration, the results show that the **radiator system has the highest operational impact from the boiler in Module B6**. This can be explained by the **lower system efficiency associated with radiator-based heating**, which typically operates at higher supply temperatures compared with radiant floor systems. Higher operating temperatures reduce boiler efficiency and increase natural gas consumption, leading to higher emissions in energy-related impact categories.

A similar trend is observed in the impact category **Resource Use – Fossils**, which is also strongly influenced by the consumption of fossil energy during the operational phase. Again, the radiant floor system shows better environmental performance due to its **lower operating temperature and improved system efficiency**, while the Radiator system remains the most impactful configuration.

In contrast, a different pattern emerges in **material-related impact categories**, such as **Resource Use – Minerals and Metals**. In this category, the **radiant floor system shows the lowest environmental impact**, while the **fan-coil system exhibits the highest impact**. The radiator system falls between the two. These differences are mainly associated with the material composition and complexity of the components used in each system.

Furthermore, these results underscore the critical role of **component selection** and system architecture in determining the overall environmental profile of a heating configuration. The inclusion of auxiliary components—such as **towel dryers** in radiant floor and fan-coil systems, or the integration of **brass-heavy manifolds**—substantially alters the life-cycle impact distribution. Consequently, system design must be evaluated not only by performance requirements but also by the specific **material composition** of the selected components. This highlights the necessity of considering the life-cycle implications of material selection during the design phase, as even ancillary components can shift the primary 'hotspots' of impact across the system's lifespan.

Overall, the comparison shows that the environmental performance of heating systems depends not only on the general system type but also on the **specific configuration and components included in the design**. Factors such as **system efficiency, operating temperature, component selection, and material composition** all influence the resulting environmental impacts.

For the specific conditions of this case study, the **radiant floor system generally demonstrates better performance in energy-related impact categories**, mainly due to its higher efficiency and lower operating temperature. However, the results also emphasize that careful design decisions during the early stages of system planning — including **proper system sizing, efficient design, and informed selection of components and materials** — play a crucial role in determining the overall environmental performance of heating systems.

2.2.5.3. Validation of results

The table below reports results from life cycle impact assessments related to climate change-fossil and non-renewable primary energy of each system in their life cycle modules. Also, it presents **ratio check for different modules indicating carbon intensity of energy use**, meaning how much CO_2 eq is emitted per unit of energy consumed.

The overall results show that almost all systems total ratio values are identical for systems. This means that **differences in environmental impacts between the systems are therefore not due to different carbon intensities, but rather due to different amounts of energy consumed** in each life cycle module. This results are expected because the systems rely on **similar energy sources, mainly natural gas and electricity**.

The production module **(A1-A3)** which is related to materials creating the components of systems, shows moderate carbon intensity. **Radiator System has highest carbon intensity** and Radiant floor System has the lowest. The reason between these differences in the ratio mostly seems for different **Non renewable primary energy use** rather than little difference between climate change-fossil.

The replacement modules **(B4)** among all the systems, have almost an identical carbon intensity ratio, even thought the non renewable primary energy values differ across systems.

The Operational Use **(B6)** shows nearly identical ratios across all systems. This confirms the systems use the **same energy carriers** therefore the carbon intensity per MJ is similar.

Table 44: Carbon intensity results from LCIA of all modules in all systems

	Radiator System			Radiant Floor System			Fancoil System		
Modules	Climate change - Fossil	Non renewable, primary energy	Ratio Check	Climate change - Fossil	Non renewable, primary energy	Ratio Check	Climate change - Fossil	Non renewable, primary energy	Ratio Check
	kg CO_2 eq/ FU	MJ/FU	kg CO_2 eq/MJ	kg CO_2 eq/ FU	MJ/FU	kg CO_2 eq/MJ	kg CO_2 eq/ FU	MJ/FU	kg CO_2 eq/MJ
A1-A3	0.004	0.058	0.074	0.002	0.036	0.057	0.003	0.043	0.069
B4	0.006	0.078	0.082	0.003	0.034	0.081	0.005	0.059	0.081
B6	0.291	4.654	0.063	0.277	4.412	0.063	0.290	4.630	0.063
C3	0.00018	0.00063	0.288	0.00018	0.00027	0.693	0.00028	0.00047	0.602
C4	0.00001	0.00003	0.272	0.00002	0.00004	0.449	0.00001	0.00002	0.285
Total	0.302	4.790	0.063	0.282	4.483	0.063	0.298	4.732	0.063

End of life modules **(C3 and C4)**, show the highest carbon intensity among other modules, however these phases usually involve very **small energy quantities**, meaning their total **contribution to environmental impact is often limited**.

The reason behind the higher order of magnitude observed in the carbon intensity ratios of modules C3 and C4 is mainly related to the specific materials involved in these phases and the very small absolute values of both climate change and non-renewable primary energy results. Although the calculated ratios appear relatively high, the overall environmental contribution of these modules remains very limited compared to the other life-cycle modules due to their extremely small absolute impact values. A deeper analysis of these modules shows that the higher ratios are **not primarily caused by increased energy consumption, but rather by climate change impacts that are not proportional to the corresponding primary energy demand**. As discussed below, this disproportion is largely attributable to **methodological limitations** embedded in the selected **Ecoinvent datasets**, particularly regarding the **treatment of embodied primary energy** and the **modeling of emissions from synthetic polymer materials**.

For **module C3**, the higher carbon intensity can be explained by the presence of **incineration processes associated with plastic-based components** within the systems, such as distribution pipes, radiant floor pipes, plastic parts of fan-coils, and plastic components within boilers. The selected Ecoinvent dataset, "Waste polyethylene {CH}|treatment of waste polyethylene, municipal incineration FAE | Cut-off, U", presents an important **methodological limitation** that must be acknowledged. The dataset defines its system boundary starting at the facility gate, with **energy values** listed as **undefined**, meaning that the embodied non-renewable primary energy of the polyethylene is not accounted for as an input to the process. Since polyethylene is a fossil derived synthetic polymer with a gross heating value of 41.63 MJ/kg, its incineration releases entirely fossil CO_2, confirmed by the dataset's reported biogenic carbon share of 0%, which is fully captured in the **climate change impact** indicator. However, because the **embodied energy content** of the material is **absent** from the primary energy accounting, the non-renewable primary energy demand associated with this module appears artificially near zero, **resulting in a disproportionately high carbon intensity ratio**. This does not reflect a genuine increase in greenhouse gas emissions per unit of energy consumed, but rather an incomplete energy balance introduced by the Cut-off system boundary approach applied to a fossil-derived waste material.

In **module C4**, where no incineration processes are involved, the higher carbon intensity ratio is again mainly linked to plastic-based components within the systems. The C4 module mainly includes **final disposal** and **landfill processes** for **materials such as steel, copper, and aluminum**, which are generally expected to show **low climate change impacts proportional to their energy demand**. Therefore, the carbon intensity ratio would normally be expected to remain within a similar range to other modules, such as A1–A3. However, a more detailed contribution analysis revealed that one specific component, namely the **distribution pipes, significantly influenced the C4 carbon intensity results.**

The **distribution pipes contain PEX (cross-linked polyethylene)**, and for the landfill stage in module C4, the selected Ecoinvent process was “Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, U”. This process was selected because **no specific end-of-life dataset for PEX pipes or polyethylene inert landfill was available within the database**. The sanitary landfill dataset was considered the closest available proxy and more appropriate than inert landfill, since PEX is a polymer-based material rather than an inert mineral material. Nevertheless, this dataset introduces **two methodological limitations** that must be critically acknowledged.

First, consistent with the C3 dataset, the **energy values** are listed as **undefined** and the system boundary begins at the facility gate, meaning the **embodied non-renewable primary energy of the polyethylene** is not included as an input. As a result, the non-renewable primary energy demand for this module is near zero, which artificially inflates the carbon intensity ratio rather than reflecting a genuine energy-carbon relationship.

Second, the dataset models **landfill gas and methane emissions** associated with polyethylene disposal, reporting a total CH_4 mass of 0.008177 kg per kg of waste, which **contribute significantly** to the **climate change impact**. However, this is methodologically questionable. Methane generation in landfills is primarily driven by the **anaerobic microbial decomposition of biogenic materials**, such as food waste or lignocellulosic matter. Polyethylene, including cross-linked polyethylene (PEX), is a synthetic, non-biogenic polymer, confirmed by the dataset's reported biogenic carbon share of 0% and an overall degradability of only 1% over 100 years. Under actual landfill conditions, PEX does not undergo meaningful anaerobic degradation and would therefore not be expected to generate significant quantities of landfill gas or methane. The methane emissions modeled by this dataset appear to be an artifact of the generic municipal solid waste sanitary landfill framework on which it is based, rather than a material-specific representation of polyethylene behavior. This likely **leads to an overestimation of the climate change impact** associated with **PEX pipe disposal** in module C4.

For example, in the fan-coil system, the **overall C4 carbon intensity ratio** was approximately **0.04** when the contribution of the **pipes was excluded**, while the **pipe component itself** showed a **carbon intensity** ratio of approximately **0.33.** Similar behavior can therefore be expected in the other systems, as they include comparable distribution pipes, while the **radiant floor system** contains an even larger quantity of similar **polymer-based piping materials**.

In summary, the **elevated carbon intensity ratios** observed in **modules C3 and C4** are not indicative of genuinely higher greenhouse gas emissions per unit of energy consumed, but rather reflect two compounding **methodological limitations**: the **omission of embodied non-renewable primary energy** from the waste input under the Cut-off system boundary, and the questionable modeling of **methane emissions from a non-biogenic synthetic polymer** using a generic municipal solid waste landfill framework. Both effects artificially depress the primary energy denominator and/or inflate the climate change numerator in the carbon intensity ratio. The absolute environmental impacts of these modules remain extremely small, and the results should therefore be interpreted with appropriate caution, recognizing that they are partly driven by dataset assumptions rather than **actual physical behavior of the materials** involved.

2.2.5.4. Sensitivity analysis

In Life Cycle Assessment, **input data** are not always exact and may **vary depending** on several factors, such as material selection, data sources (e.g., manufacturer claims, databases, or Environmental Product Declarations), and modeling assumptions. These variations can influence the final impact assessment results and introduce uncertainty into the analysis.

In this study, the parameter selected for **sensitivity analysis** is the **boiler efficiency**, which was identified as a key variable parameter during the **energy modeling phase** using IESVE, where efficiencies are calculated based on **Higher Heating Value (HHV)**. As presented in the Material and Methods section, boiler efficiency is not constant but **fluctuates** over the course of the year depending on operating conditions. The **energy simulation provided hourly timestep outputs** over the **annual simulation period**, recording the **boiler efficiency value active at each timestep**. **Table 45** reports the **resulting frequency distribution for each system**, where the frequency column indicates the number of simulation timesteps (hours) at which each efficiency value was recorded. The total number of recorded timesteps **differs slightly** across systems, as only timesteps during which the **boiler was actively operating** are included, excluding periods of zero demand. It should be noted that Table 45 reports raw occurrence counts rather than normalized probabilities; the frequencies are therefore not expected to sum to 1,000 or 100, but rather reflect the **actual number of active boiler operating hours** within the annual simulation.

As shown in Table 45, the three heating systems exhibit notably **different efficiency distributions**, reflecting their **distinct thermal demand profiles and control logic**. The **radiator system** records the **widest efficiency range**, spanning from 88.5% to 93% across **920 total active timesteps**, with 90% being the most frequently occurring value (186 timesteps). The **radiant floor system** operates within a much narrower band, recording **1,092 active timesteps** concentrated at only two efficiency values: 95.5% (845 timesteps) and 96% (247 timesteps), reflecting its **more stable and consistent operating conditions**. The **fancoil system** similarly shows a narrow distribution, with **1,143 active timesteps** recorded at 91.5% (217 timesteps) and 92% (926 timesteps). The differences in total active timesteps across systems are physically meaningful, as systems with **higher heating loads or less thermally efficient distribution circuits** naturally accumulate **more boiler operating hours** over the course of the year.

In the base LCA model, the **most frequently occurring efficiency value** for each system was selected as a representative input to calculate natural gas consumption in Module B6. While this approach provides a reasonable approximation, it introduces an inherent simplification, as it does not fully capture the variability of real-world operation. In practice, boiler efficiency fluctuates over time, directly affecting fuel consumption and associated emissions. Therefore, relying on a single efficiency value may lead to an incomplete representation of the actual environmental impacts under variable operating conditions.

Table 45: Boiler efficiency values and their observed occurrence frequency across annual IESVE simulation timesteps for each heating system

Radiator System		Radiant Floor System		Fancoil System	
Efficiency value	Frequency	Efficiency value	Frequency	Efficiency value	Frequency
87.5	0	92	0	87	0
88	0	92.5	0	87.5	0
88.5	2	93	0	88	0
89	92	93.5	0	88.5	0
89.5	154	94	0	89	0
90	186	94.5	0	89.5	0
90.5	90	95	0	90	0
91	158	95.5	845	90.5	0
91.5	54	96	247	91	0
92	160	96.5	0	91.5	217
92.5	21	97	0	92	926
93	3	97.5	0	92.5	0
100	0	100	0	100	0

The boiler efficiency values obtained from the IESVE energy simulation do not enter SimaPro directly. Instead, they are used to calculate the **natural gas consumption,** which represents the actual variable input to the LCA model. Specifically, for each heating system, the **gas input** (expressed in Nm^3 per functional unit) is derived by combining the boiler efficiency with a set of fixed parameters, including the apartment floor area, the energy demand of each heating system, the Reference Study Period (RSP), the Higher Heating Value (HHV) of natural gas, and the appropriate unit conversion factors, all normalized to the defined functional unit. As **boiler efficiency increases**, **less natural gas** is required to deliver the same amount of useful heat, resulting in lower gas input values and consequently **lower environmental impacts** across all impact categories. It is therefore this final gas input value, computed for each efficiency scenario, that is entered into SimaPro to calculate the corresponding environmental impacts.

In the context of LCA, **uncertainty** can be characterized using statistical parameters such as **probability distributions, mean values, and standard deviations,** which describe the spread and variability of data. Various methods exist to evaluate the influence of such variability on LCA results, including **Monte Carlo** simulations and **One-At-a-Time (OAT) sensitivity analysis**, as described in the methodological framework of this study.

In this study, a **two-step approach** was adopted. As a first step, an **OAT sensitivity analysis** was performed by **calculating the environmental impacts** corresponding to each **observed efficiency value** for each heating system. Each efficiency value was individually converted into its corresponding gas input using the formula described above, and the resulting gas input was entered into SimaPro to obtain the impact category results. This allowed a direct and transparent evaluation of how discrete variations in boiler efficiency propagate through the gas consumption calculation and ultimately affect the LCA results. The selected efficiency values and their corresponding gas inputs and impact results are reported in Table 46.

Table 46: Selected Impact categories results within different Boielr Efficiencies

	Variables		Impact categories (Module B6 of Boiler)			
	Boiler Efficiency	Gas Input	Climate change - Fossil	Resource use, fossils	Resource use, minerals and metals	Water use
	%	(Nm^3/FU)	kg CO_2 eq/FU	MJ/FU	kg Sb eq/FU	m^3 depriv./FU
Radiator System	88.5	0.101	2.97E-01	4.28E+00	9.55E-08	4.25E-03
	90	0.099	2.91E-01	4.19E+00	9.37E-08	4.17E-03
	93	0.096	2.82E-01	4.07E+00	9.08E-08	4.04E-03
Radiant floor system	95.5	0.093	2.75E-01	3.94E+00	8.80E-08	3.91E-03
	96	0.092	2.71E-01	3.90E+00	8.70E-08	3.87E-03
Fancoil system	91.5	0.097	2.85E-01	4.11E+00	9.18E-08	4.08E-03
	92	0.096	2.83E-01	4.07E+00	9.08E-08	4.04E-03

It should be noted that, due to software limitations, a full probabilistic Monte Carlo analysis, which would have allowed the simultaneous propagation of uncertainty across all input parameters, could not be performed within the available SimaPro version. The approach described here therefore represents a structured approximation, combining deterministic scenario comparison with a statistical characterization of the observed efficiency distributions, as described in the following step.

As a second step, **a statistical approach** was applied to account for the **different frequencies of occurrence** of **efficiency values** observed across the year. Since the efficiency values do not occur with equal probability, as clearly shown in Table 45, where for example the radiator system records 186 occurrences at 90% but only 3 at 93% , a simple arithmetic mean would not be representative. Therefore, a probability-weighted distribution was constructed for each heating system, using the frequency of each observed efficiency value as its statistical weight.

The **weighted mean of the gas input** was calculated as:

$$\mu = \frac{\sum(x_i * f_i)}{\sum f_i} \tag{28}$$

Where x_i is the gas input value corresponding to each efficiency value, and f_i is its frequency of occurrence.

Since the gas input values occur with different frequencies, the standard deviation was also computed as a **weighted standard deviation**:

$$\sigma = \sqrt{\frac{\sum f_i * (x_i - \mu)^2}{\sum f_i}} \tag{29}$$

The resulting weighted mean and weighted standard deviation for each system are reported in Table 47 and Table 48.

Table 47: Weighted mean values with standard deviation for each system

System	Mean − 2SD	Weighted Mean of Gas Input (Nm^3/FU)	Mean + 2SD
Radiator	0.0961	0.0983	0.1005
Radiant floor	0.0920	0.0925	0.0929
Fan coil	0.0957	0.0961	0.0966

A **normal distribution** was assumed for this analysis. This choice is justified by the nature of the observed data: the efficiency values are **bounded within a relatively narrow** and **approximately symmetric range around the most frequently occurring value** for each system. It should however be acknowledged that, given the **limited number of distinct efficiency values**, particularly for the radiant floor and fancoil systems, which exhibit only two non-zero frequency values, a formal statistical normality test could not be robustly applied. The normal distribution assumption therefore represents a reasonable but simplified approximation, and this constitutes a limitation of the analysis.

To characterize the **uncertainty range**, a **95% confidence interval** was adopted, defined as **mean ± 2SD**, consistent with standard practice in LCA uncertainty analysis. The resulting gas input ranges for each system are summarized in Table 47, showing the mean, mean − 2SD, and mean + 2SD values. These three values were subsequently entered into SimaPro to calculate the corresponding impact category results reported in Table 48, reflecting the expected environmental performance of each heating system under variable operating conditions.

Table 48: Selected Impact category results within probability weighted normal distribution

		Impact categories (Module B6 of Boiler)			
		Climate change - Fossil	Resource use, fossils	Resource use, minerals and metals	Water use
		kg CO_2 eq/FU	MJ/FU	kg Sb eq/FU	m^3 depriv./FU
Radiator System	Mean + 2SD	2.97E-01	4.28E+00	9.55E-08	4.25E-03
	Mean	2.90E-01	4.15E+00	9.27E-08	4.12E-03
	Mean − 2SD	2.83E-01	4.07E+00	9.08E-08	4.04E-03
Radiant floor system	Mean + 2SD	2.74E-01	3.93E+00	8.78E-08	3.91E-03
	Mean	2.72E-01	3.92E+00	8.75E-08	3.89E-03
	Mean − 2SD	2.71E-01	3.90E+00	8.71E-08	3.87E-03
Fancoil system	Mean + 2SD	2.84E-01	4.09E+00	9.13E-08	4.06E-03
	Mean	2.83E-01	4.07E+00	9.10E-08	4.05E-03
	Mean − 2SD	2.82E-01	4.06E+00	9.06E-08	4.03E-03

The results of both the **OAT sensitivity analysis** (Table 46) and the **probability-weighted statistical analysis** (Table 48) consistently indicate that, even when accounting for the full range of observed efficiency variability, the overall ranking of the three heating systems remains **unchanged** across all considered impact categories. The **radiant floor system** consistently shows the **lowest environmental impacts**, followed by the fancoil system, while the **radiator system** exhibits the **highest impacts**. This finding holds true both for the deterministic efficiency scenarios and for the statistically weighted mean values with their associated uncertainty ranges (mean ± 2SD).

Furthermore, the **magnitude of variation** in impact results due to **efficiency fluctuations** remains moderate across all systems, as evidenced by the full uncertainty range reported in **Table 48**. For the **radiator system**, which exhibits the **widest efficiency range** (88.5%–93%), the **climate change impact** spans from 2.83E-01 kg CO_2 eq/FU (Mean − 2SD) to 2.97E-01 kg CO_2 eq/FU (Mean + 2SD), representing a variation of approximately **5%** around the weighted mean. For the **radiant floor system**, the **narrower operational range** results in a substantially smaller spread, with **climate change** impacts ranging from 2.71E-01 to 2.74E-01 kg CO_2 eq/FU, corresponding to a variation of less than **1.5%**. The **fancoil system** similarly shows minimal sensitivity, with **climate change** results ranging from 2.82E-01 to 2.84E-01 kg CO_2 eq/FU, a variation of less than **1%**. Consistent patterns are observed across all other impact categories. These findings indicate that the LCA model is relatively **insensitive to boiler efficiency fluctuations** within the observed operational range, and that the system ranking, with the **radiant floor system** consistently showing the **lowest impacts** and the **radiator system** the **highest**, remains robust under the full extent of realistic variability conditions.

It should however be noted that this sensitivity analysis focuses solely on the **boiler-related natural gas consumption** within **Module B6**. The total operational impact of each heating system also includes **auxiliary electricity consumption** from system-specific components, such as towel dryers in the radiator system and fan coil units in the fancoil system, which were not subject to this sensitivity analysis. While boiler efficiency variability has been shown to exert only a limited influence on overall results, these auxiliary contributions represent an additional source of variability that falls outside the scope of the present analysis and should be considered when interpreting system-level comparisons in a broader operational context.

2.2.5.5. Multi-criteria analysis: Ternary diagram

In this section, a **multi-criteria analysis** of the total system's impacts is conducted across three main categories to facilitate a comprehensive comparative understanding. To achieve this, **weighting results** were extracted from SimaPro for all three systems across all impact categories. Based on these results, three **significant impact categories** were selected for detailed evaluation: **Climate Change, Resource Use (minerals and metals), and Photochemical Ozone Formation.** Although Photochemical Ozone Formation appeared as the fourth most significant category in the weighted results, it was prioritized over Resource Use (fossils). This decision was made because fossil resource consumption is intrinsically linked to combustion and fossil fuel use, which is already adequately represented by the Climate Change results; therefore, to ensure a diverse environmental effect analysis and avoid redundant indicators, these three distinct categories were utilized.

Table 49:Weighting results of impact categories in all systems

Impact category	Unit	Radiator system	Radiant floor system	Fancoil system
Acidification	μPt	0.27	0.24	0.29
Climate change	μPt	8.430	7.871	8.318
Eutrophication, marine	μPt	0.09	0.08	0.09
Eutrophication, freshwater	μPt	0.21	0.18	0.23
Eutrophication, terrestrial	μPt	0.12	0.11	0.12
Ozone depletion	μPt	0.01	0.01	0.01
Photochemical ozone formation	μPt	0.651	0.600	0.647
Resource use, fossils	μPt	5.53	5.18	5.47
Resource use, minerals and metals	μPt	1.219	1.168	1.491
Water use	μPt	0.05	0.06	0.09

The **analytical process** began with the **normalization** of the **characterization outcomes** to transform disparate units into a dimensionless comparative scale. First, the environmental impact values for the selected categories, Climate Change, Resource Use (minerals and metals), and Photochemical Ozone Formation, were extracted directly from the characterization results, ensuring consistency of **physical meaning and avoiding the use of weighting factors.**

Table 50: Characterization results of selected impact categories for each system

System	Climate change (kg CO2 eq)	Resource use, minerals and metals (kg Sb eq)	Photochemical ozone formation (kg NMVOC eq)
Radiator system	3.02E-01	1.03E-06	5.56E-04
Radiant Floor system	2.82E-01	9.84E-07	5.13E-04
Fancoil system	2.98E-01	1.26E-06	5.53E-04

For each impact category, the **maximum and minimum values** across the three systems were identified, and the corresponding range was calculated. These values were then used to **normalize the data** using a **“distance-to-target”** approach, in which each system’s performance was scaled between 0 (worst performance) and 1 (best performance). This normalization ensured comparability across impact categories with different units and magnitudes.

$$Si = \frac{x_{max} - x_i}{x_{max} - x_{min}} \qquad (30)$$

where x_i represents the raw impact value, x_{max} is the maximum (worst) value in the set, and x_{min} is the minimum (best) value.

Subsequently, for each system, the normalized values were converted into **ternary proportions** by dividing each category value by the sum of all three normalized impact scores for that system. This step ensured that the sum of the three components **equaled one**, fulfilling the requirement for representation in a ternary plot.

Finally, the resulting proportions were transformed into **Cartesian coordinates** using standard ternary plot relationships, allowing each system to be positioned within the **triangular diagram.** This procedure enabled a consistent and transparent visualization of the relative environmental performance of each system across the three selected impact categories.

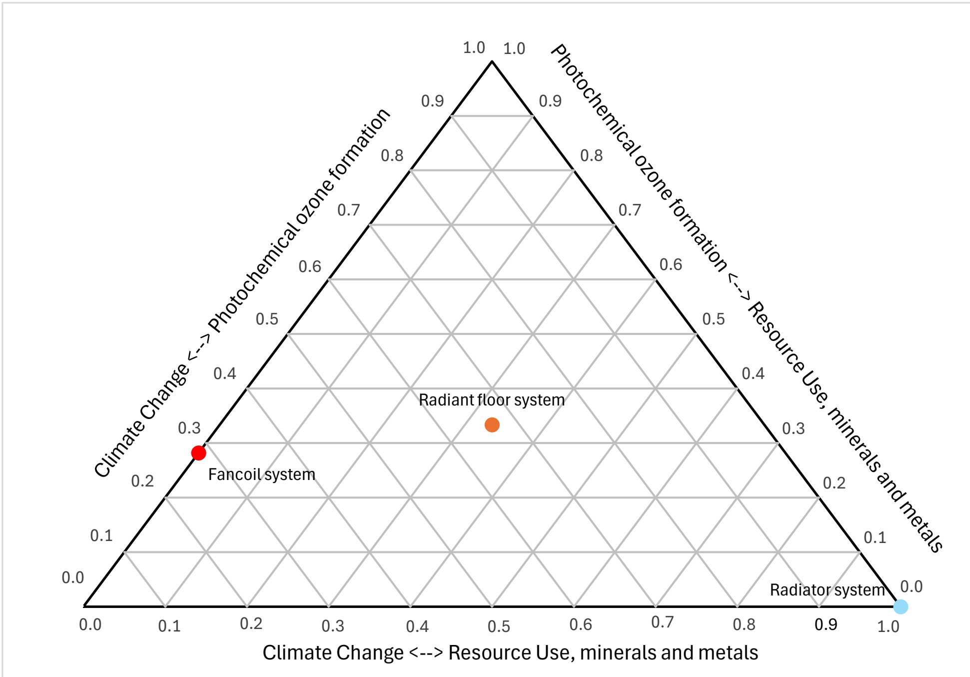

Figure 46: Ternary diagram of three heating systems

The **interpretation of the resulting ternary plot** reveals distinct environmental profiles for each technology. The **Radiant Floor system** is positioned at the exact **centroid of the plot**. This equilibrium is a mathematical result of the system achieving the **minimum impact values across all three categories**, thereby representing the **most balanced** and superior alternative in this multi-criteria framework. Conversely, the **Radiator system** is located at the **vertex corresponding to Resource Use**. This indicates that the system represents the **worst-case performance for both Climate Change and Photochemical Ozone Formation**, leaving its comparative advantage entirely concentrated in mineral and metal preservation. The **Fancoil system** is situated on the axis between Climate Change and Photochemical Ozone Formation; while it demonstrates **atmospheric benefits** relative to the Radiator system, it **fails** to provide any comparative advantage in terms of **resource use**. Ultimately, the analysis confirms that the **Radiant Floor system** provides an **optimized environmental profile**, whereas the Radiator and Fancoil systems necessitate significant trade-offs in at least two of the three critical impact categories.

2.2.5.6. Limitations and Recommendations

Despite the comprehensive framework adopted in this study, several limitations should be acknowledged when interpreting the results.

A primary source of uncertainty lies in the **Life Cycle Inventory data**. For each heating system and its components, material types and quantities were primarily derived from technical data sheets provided by manufacturers. However, such data were not always fully available or sufficiently detailed, and in some cases, certain components or material specifications had to be approximated. This limitation introduces uncertainty into the inventory modeling and, consequently, into the final environmental impact results.

In addition, the study simplifies the **representation of manufacturing processes**. Due to the complexity and data intensity of Life Cycle Assessment, it was not feasible to model all detailed production stages of each component. For example, processes such as raw material extraction, steel processing for radiators, component assembly, transportation to the construction site, and packaging were not always explicitly modeled. Similarly, **end-of-life scenarios** were not consistently supported by detailed data, and assumptions were required. These simplifications may lead to under- or over-estimation of impacts across life cycle stages.

Another limitation is related to the **level of detail in impact assessment interpretation**. Although a full set of impact categories was calculated within the Life Cycle Impact Assessment phase, only selected key indicators were analyzed in depth. While this approach supports clearer interpretation, it may overlook potentially relevant environmental trade-offs across less-discussed impact categories.

Finally, as highlighted in the sensitivity analysis, the study relies on **deterministic assumptions for key parameters**, such as boiler efficiency. While representative values were selected based on simulation outputs, real-world performance varies over time, and this variability is not fully captured, contributing further to uncertainty in operational impact estimation

Based on the identified limitations, several recommendations can be proposed to enhance future research in this field.

First, improving the quality and completeness of inventory data is essential. With the introduction of new European regulations such as the **Ecodesign for Sustainable Products Regulation (ESPR)** and the **Construction Products Regulation (CPR)**, future studies will benefit from the implementation of **digital product passports**. These regulatory frameworks mandate the provision of standardized, transparent data regarding material composition, manufacturing processes, and environmental profiles for building components. Access to such verified, product-specific information would significantly reduce the current reliance on generic proxy datasets, thereby minimizing modeling uncertainty and improving the overall reliability of LCA results.

Secondly, future analyses could expand the scope by incorporating **more detailed modeling of life cycle stages**, including manufacturing processes, transportation, packaging, and end-of-life scenarios. A more comprehensive representation of these stages would provide a more accurate picture of total environmental impacts.

Another important recommendation is to conduct **comparative assessments across different product designs and configurations**. For instance, evaluating boilers with varying material compositions or alternative designs of emission and distribution components (e.g., radiators, pipes, or fan coils) could reveal how design choices influence environmental performance.

Furthermore, future research could explore **alternative system configurations**, such as replacing conventional boilers with heat pump technologies, to assess potential environmental benefits under different energy supply scenarios. This would support decision-making aligned with decarbonization strategies.

Finally, a more comprehensive interpretation could be achieved by performing **in-depth analysis across a broader range of impact categories**, ensuring that potential trade-offs between environmental indicators are fully understood.

3. Conclusion

This study aimed to investigate the **environmental performance** of different **Heating, Ventilation and Air Conditioning system** configurations within a **residential case study**, with a particular focus on the **heating emission and distribution systems**. By applying a comprehensive **Life Cycle Assessment** framework, the research addressed a critical gap in existing literature, where most studies prioritize heat generation technologies while neglecting the material-intensive components such as radiators, pipes, manifolds, and fan-coil units.

The analysis was based on a representative 83 m² apartment located in **Milan**, where three heating configurations, **radiator, radiant floor, and fan-coil systems**, were modeled and evaluated. A dynamic energy simulation using **IESVE** enabled accurate estimation of heating demand and system performance under consistent boundary conditions. In addition, the energy modeling phase provided the basis for system design, including component sizing, operating conditions, and the quantification of materials. This was essential for the LCA, ensuring that the inventory reflected realistic and detailed system configurations.

The preliminary analysis identified a peak heating load of 3.67 kW, with a design load of **2.5 kW** covering 98% of **annual demand**. The total annual heating requirement was 2289 kWh (27.58 kWh/m²), mainly driven by transmission and ventilation losses. While theoretical heating demand was identical across systems, differences emerged in actual performance. The **radiant floor system** showed the **most consistent behavior** and closest match between generated and delivered energy, whereas the radiator system operated in shorter, more intense cycles with higher energy input, and the fan-coil system exhibited longer operating durations and greater inefficiencies between generation and emission.

Operating temperature proved to be a key factor influencing performance. Low-temperature radiant floor systems (25–30°C) achieved the highest and most stable boiler efficiencies (95–96%), while fan-coils (40–50°C) reached intermediate efficiencies and required higher auxiliary electricity due to fan use. Radiators (50–60°C) showed lower and more variable efficiencies (88–92%). From a thermal comfort perspective, the radiant floor system provided the most stable indoor conditions due to its thermal inertia and higher radiant heat contribution, while fan-coils resulted in more noticeable temperature fluctuations and radiators showed moderate variability. These findings highlight the strong link between system design, operational behavior, energy efficiency, and indoor comfort, forming a robust basis for the subsequent environmental assessment.

The environmental assessment followed the **ISO 14040/14044** framework, using **SimaPro** and the Ecoinvent database, with results normalized to a **functional unit of 1 kWh of delivered thermal energy** over a 50-year reference study period. The system boundaries included product, replacement, operational energy, end-of-life, and beyond-boundary benefits (Modules A1–A3, B4, B6, C3–C4, and D), providing a comprehensive life-cycle perspective. A critical finding of this life-cycle perspective was the significance of the Replacement Stage (B4). Because technical systems often have a shorter Estimated Service Life (ESL) than the building, Module B4 emerged as a major hotspot, accounting for 36–64% of the total embodied environmental impacts over the building's life cycle.

The results clearly identified **Module B6 (operational energy use)** as the dominant contributor to climate-related impacts, accounting for more than 90% of impacts in categories such as Climate Change (Fossil) and Fossil Resource Use. However, for material-related impact categories, such as Resource Use (Minerals and Metals) and Freshwater Eutrophication, the **product stage (A1–A3)** and **replacement stage (B4)** were the primary contributors. Across all systems, these modules collectively accounted for the majority of impacts in these categories—for example, up to 86% in the fan-coil system for resource use and approximately 65% for freshwater eutrophication. Furthermore, the analysis revealed that environmental impact is often disproportionate to mass; for instance, brass valves can represent 9–36% of a system's total embodied impact while only accounting for 2% of its total weight.

The inclusion of **Module D (benefits beyond the system boundary)** further emphasized the importance of material recovery and recycling. By applying the avoided burden approach, significant environmental credits were observed, particularly in material-related categories. Recycling rates of up to 97% for metals such as steel, aluminum, and copper resulted in substantial reductions, offsetting approximately 70–74% of impacts in resource use categories. However, the influence of Module D on climate-related impacts remained limited, as these are primarily driven by operational energy consumption.

Among the evaluated systems, the **radiant floor configuration** consistently demonstrated **the lowest environmental impact** across most categories, confirming that system architecture and operating temperature are key determinants of sustainability performance. Its superior performance is primarily driven by low-temperature operation (25–30°C), which enables stable high boiler efficiency (95–96%) and reduces operational impacts (Module B6). In addition, its relatively simple design, based mainly on durable polymer pipes (PEX) with long service life and no required replacements, minimizes embodied impacts. This is reflected in its lowest Climate Change and Fossil Resource Use indicators, as well as a high resource recovery potential in Module D.

In contrast, the **fan-coil system** can be identified as a material-intensive hotspot. Its mechanical complexity and reliance on steel, copper, and aluminum components result in the highest impacts in resource depletion categories. Furthermore, the need for continuous auxiliary electricity to operate integrated fans increases its operational footprint. The combined contribution of production (A1–A3) and replacement phases (B4) dominates its environmental profile, highlighting the burden of complex system design.

The **radiator system**, while simpler in construction, performs as an operational hotspot due to its high-temperature requirements (50–60°C), which limit boiler efficiency (88–92%) and increase fuel consumption. Consequently, it records the highest impacts in Climate Change and Fossil Resource Use categories. Additionally, its steel-intensive composition contributes to elevated impacts in categories such as freshwater eutrophication.

Considering the results of the Life Cycle Assessment and the overall objective of this study, an important question is whether emission and distribution systems should be explicitly considered in HVAC system design and environmental assessments, and to what extent their associated burdens are significant.

To address this, summary tables were developed for each system configuration, categorizing impact categories based on the relative contribution of emission and distribution systems to the total environmental impact. Contributions were classified into four ranges: **below 5% (negligible), 5–10% (minor), 10–20% (moderate), and above 20% (significant)**.

Although the results vary across the three configurations, radiator, radiant floor, and fan-coil systems, a consistent pattern emerges. For impact categories primarily driven by fossil fuel consumption, such as Climate Change (Fossil) and Resource Use (Fossils), the contribution of emission and distribution systems is generally negligible, indicating that these impacts are dominated by the generation phase.

In contrast, for material- and emission-related categories, including **acidification, freshwater eutrophication, and resource use (minerals and metals)**, emission and distribution systems contribute more substantially, often exceeding relevance thresholds and playing a meaningful role in the overall environmental burden. These findings demonstrate that the importance of emission and distribution systems is highly dependent on the impact category considered.

Therefore, limiting LCA analyses to generation systems or focusing solely on fossil-related indicators provides an incomplete perspective. A comprehensive evaluation of HVAC systems must include emission and distribution components to capture the full range of environmental impacts and avoid underestimating the significance of material-intensive processes.

Table 51: Radiator configuration, Absolute and Relative results of systems in each impact category

Impact category	Unit	emission system		distribution system		generation system		Total
emission and distibution percentage < 5%								
Ozone depletion	kg CFC11 eq	6.00E-11	0.84%	1.36E-11	0.19%	7.05E-09	98.97%	7.12E-09
Resource use, fossils	MJ	6.93E-02	1.60%	1.12E-02	0.26%	4.24E+00	98.14%	4.32E+00
Climate change - Fossil	kg CO2 eq	6.26E-03	2.07%	6.43E-04	0.21%	2.95E-01	97.72%	3.02E-01
Photochemical ozone formation	kg NMVOC eq	2.02E-05	3.63%	4.00E-06	0.72%	5.32E-04	95.66%	5.56E-04
10% < emission and distibution percentage < 20%								
Eutrophication, marine	kg N eq	5.69E-06	9.42%	8.98E-07	1.49%	5.37E-05	89.09%	6.03E-05
Eutrophication, terrestrial	mol N eq	5.78E-05	10.06%	1.07E-05	1.87%	5.06E-04	88.07%	5.74E-04
Acidification	mol H+ eq	2.58E-05	10.81%	1.20E-05	5.02%	2.01E-04	84.18%	2.39E-04
Resource use, minerals and metals	kg Sb eq	4.17E-08	4.06%	1.36E-07	13.20%	8.50E-07	82.74%	1.03E-06
Climate change - Land use and LU change	kg CO2 eq	3.23E-06	6.74%	4.35E-06	9.09%	4.03E-05	84.17%	4.79E-05
20% < emission and distibution percentage								
Water use	m3 depriv.	1.21E-03	16.71%	3.75E-04	5.18%	5.65E-03	78.11%	7.24E-03
Eutrophication, freshwater	kg P eq	2.42E-06	19.76%	9.07E-07	7.39%	8.94E-06	72.85%	1.23E-05
Climate change - Biogenic	kg CO2 eq	9.41E-05	81.07%	2.33E-06	2.01%	1.96E-05	16.92%	1.16E-04

Table 52: Radiant Floor configuration, Absolute and Relative results of systems in each impact category

Impact category	Unit	emission system		distribution system		generation system		Total
emission and distibution percentage < 5%								
Ozone depletion	kg CFC11 eq	7.56E-11	1.13%	1.89E-12	0.03%	6.62E-09	98.84%	6.70E-09
Climate change - Fossil	kg CO2 eq	3.31E-03	1.17%	1.70E-04	0.06%	2.79E-01	98.76%	2.82E-01
Resource use, fossils	MJ	5.56E-02	1.38%	2.22E-03	0.05%	3.99E+00	98.57%	4.04E+00
Photochemical ozone formation	kg NMVOC eq	1.07E-05	2.09%	2.02E-06	0.39%	5.00E-04	97.52%	5.13E-04
Climate change - Land use and LU change	kg CO2 eq	9.82E-07	2.47%	3.38E-07	0.85%	3.85E-05	96.68%	3.98E-05
5% < emission and distibution percentage < 10%								
Eutrophication, marine	kg N eq	2.22E-06	4.16%	5.18E-07	0.97%	5.06E-05	94.87%	5.34E-05
Eutrophication, terrestrial	mol N eq	2.34E-05	4.61%	6.99E-06	1.38%	4.77E-04	94.02%	5.07E-04
10% < emission and distibution percentage < 20%								
Acidification	mol H+ eq	1.32E-05	6.17%	9.43E-06	4.42%	1.91E-04	89.41%	2.13E-04
Eutrophication, freshwater	kg P eq	8.09E-07	8.00%	7.51E-07	7.43%	8.55E-06	84.58%	1.01E-05
Resource use, minerals and metals	kg Sb eq	3.60E-08	3.66%	1.29E-07	13.10%	8.19E-07	83.24%	9.84E-07
20% < emission and distibution percentage								
Water use	m3 depriv.	2.05E-03	27.11%	1.63E-04	2.15%	5.35E-03	70.73%	7.57E-03
Climate change - Biogenic	kg CO2 eq	1.96E-04	91.02%	7.96E-07	0.37%	1.86E-05	8.61%	2.15E-04

Table 53: Fancoil configuration, Absolute and Relative results of systems in each impact category

Impact category	Unit	emission system		distribution system		generation system		Total
emission and distibution percentage < 5%								
Ozone depletion	kg CFC11 eq	1.82E-10	2.59%	1.11E-11	0.16%	6.84E-09	97.25%	7.03E-09
Climate change - Fossil	kg CO2 eq	1.01E-02	3.38%	5.44E-04	0.18%	2.87E-01	96.44%	2.98E-01
Resource use, fossils	MJ	1.46E-01	3.42%	9.32E-03	0.22%	4.12E+00	96.36%	4.27E+00
5% < emission and distibution percentage < 10%								
Photochemical ozone formation	kg NMVOC eq	3.22E-05	5.82%	3.62E-06	0.65%	5.17E-04	93.52%	5.53E-04
10% < emission and distibution percentage < 20%								
Eutrophication, marine	kg N eq	7.49E-06	12.33%	8.28E-07	1.36%	5.24E-05	86.30%	6.07E-05
Eutrophication, terrestrial	mol N eq	8.18E-05	13.97%	1.01E-05	1.72%	4.94E-04	84.31%	5.86E-04
20% < emission and distibution percentage								
Climate change - Land use and LU change	kg CO2 eq	8.91E-06	16.95%	3.49E-06	6.64%	4.02E-05	76.41%	5.26E-05
Acidification	mol H+ eq	5.32E-05	20.20%	1.17E-05	4.43%	1.99E-04	75.37%	2.63E-04
Resource use, minerals and metals	kg Sb eq	2.58E-07	20.53%	1.37E-07	10.93%	8.61E-07	68.54%	1.26E-06
Eutrophication, freshwater	kg P eq	3.54E-06	26.43%	8.92E-07	6.67%	8.95E-06	66.90%	1.34E-05
Water use	m3 depriv.	5.63E-03	48.86%	3.33E-04	2.89%	5.56E-03	48.25%	1.15E-02
Climate change - Biogenic	kg CO2 eq	5.80E-04	96.47%	2.01E-06	0.34%	1.92E-05	3.20%	6.01E-04

Taken together, the integration of **dynamic energy modeling** and **Life Cycle Assessment** provides a comprehensive understanding of HVAC system performance that goes beyond isolated evaluation approaches. The energy modeling results highlighted clear differences among systems: the **radiant floor system** achieved the **highest and most stable efficiencies** and **thermal comfort** due to **low-temperature operation**, the radiator system showed higher energy input with less efficient and more variable performance, and the fan-coil system exhibited longer operating durations and additional electrical demand. These operational differences are directly reflected in the LCA outcomes. The **radiant floor system**, combining efficient operation with a simple and durable material configuration, consistently showed the **lowest environmental impacts**. In contrast, the radiator system emerged as an operational hotspot due to higher fuel consumption, while the fan-coil system acted as a material-intensive hotspot because of its complex components and higher embodied impacts. At the same time, the dominance of operational energy (Module B6) in climate-related categories aligns with efficiency differences observed in energy modeling, whereas the importance of production and replacement stages (A1–A3 and B4) reflects system design and material intensity. This combined perspective demonstrates that system performance cannot be assessed solely based on energy efficiency or material impacts in isolation, but rather through their interaction. Consequently, achieving optimal environmental performance requires a **balance** between low operational demand, material simplicity, and long-term durability, providing a coherent basis for the broader discussion and implications that follow.

The findings of this study highlight the growing importance of **embodied emissions** in the building sector. As operational energy demand decreases due to improved building efficiency, the relative contribution of materials and technical systems becomes increasingly significant. Ignoring these aspects can lead to incomplete assessments and potential burden shifting between impact categories.

Despite its contributions, the study is subject to several limitations. The inventory phase relied heavily on manufacturer technical datasheets, which were sometimes incomplete or unavailable, introducing uncertainty into the analysis. Additionally, certain life-cycle stages, such as transportation, installation, and detailed manufacturing processes, were excluded or simplified. The results are also context-specific, reflecting the climatic conditions of Milan and assumptions such as boiler efficiency, and may therefore vary under different conditions.

Future research should focus on improving data accuracy through sources such as **Digital Product Passports**, which are expected to enhance transparency under upcoming European regulations. Expanding the system boundaries to include additional technologies, such as heat pumps, as well as incorporating more detailed modeling of transport, packaging, and end-of-life scenarios, would further strengthen the analysis. Moreover, exploring a wider range of impact categories would provide a more comprehensive understanding of environmental trade-offs.

In conclusion, this research demonstrates that the environmental performance of HVAC systems cannot be fully understood without a detailed assessment of emission and distribution components. The results provide valuable insights for designers, engineers, and policymakers, supporting more informed decision-making toward sustainable building design. Ignoring such life-cycle considerations may lead to misleading conclusions and suboptimal system choices, whereas integrating them enables a more holistic and accurate evaluation of environmental impacts.

Acknowledgment

The completion of this thesis would not have been possible without the support and contribution of a few people, to whom I would like to express my sincere gratitude.

- First and foremost, I would like to thank my supervisor, **Professor Jacopo Famiglietti**, for his guidance, patience, and dedication throughout the entire duration of this thesis. From the very first day, he provided clear directions and shared his knowledge and expertise generously, playing a fundamental role in shaping this work and leading it to its final results.
- I would also like to extend my gratitude to my co-supervisor, **Luca Pacileo**, for his valuable support and constructive input across different aspects of this project, which contributed significantly to its development.
- I am sincerely grateful to my **family and friends** for their unwavering encouragement and belief in me throughout these years. Their support never wavered, and their presence made a meaningful difference during both the demanding and rewarding moments of this journey.
- Finally, I would like to acknowledge **Politecnico di Milano** for the academic foundation and opportunities it has provided. Being admitted to this university marked the starting point of my professional formation, and this thesis stands as the result of everything that began on that first day.

Looking back, this has been a challenging yet deeply rewarding experience. I am grateful to everyone who was part of it, and I hope this work reflects the effort, dedication, and learning that went into it.

Mahsa Nasiribavili

July 2026

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Annex

Table 54: Module D1 assumed values for recycling and incineration

Module D1,material Recycling		
Recycling efficiency and recycled content	U.M.	Amount
Recycled steel in input	%	50%
Recycled copper in input	%	10%
Recycled aluminum input	%	20%
Recycled plastics in input	%	30%
Recycling efficiency steel	%	81%
Recycling efficiency copper and aluminum	%	98%
Q_{Rout}/Q_{sub}	-	1
Module D1,incineration with energy recovery	U.M.	Amount
Lower Heating Value	kWh / kg	11
X_{INC} heat	%	0.27
X_{INC} electricity	%	0.2

Table 55: Radiator System-total radiators dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	9.56E-04
A1-3	Paint (Satin)	ecoinvent process	Powder coat, steel {RER}| powder coating, steel | Cut-off, U	m2 / fU	8.75E-05
C3	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {Europe without Switzerland}| treatment of metal scrap, mixed, for recycling, unsorted, sorting | Cut-off, U	kg / fU	9.56E-04
C4	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	2.87E-05
C4	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	3.66E-04
B4 (A1-3)	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	1.59E-03
B4 (A1-3)	Paint (Satin)	ecoinvent process	Powder coat, steel {RER}| powder coating, steel | Cut-off, U	m2 / fU	1.46E-04
B4 (C3)	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {Europe without Switzerland}| treatment of metal scrap, mixed, for recycling, unsorted, sorting | Cut-off, U	kg / fU	1.59E-03
B4 (C4)	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	4.78E-05
B4 (C4)	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	6.10E-04

Table 56: Radiant Floor System-total radiant floor pipes dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	PEX-a pipe, 5-layer with EVOH oxygen barrier (16×2.0 mm)	ecoinvent process	Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate | Cut-off, U	kg / fU	1.73E-04
C3	PEX to waste processing (incineration)	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration FAE | Cut-off, U	kg / fU	2.59E-05
C4	PEX to landfill	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, U	kg / fU	1.47E-04

Table 57:Fancoil System-total fancoils dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	2.79E-04
A1-3	Copper	ecoinvent process	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	kg / fU	8.05E-06
A1-3	Aluminum	ecoinvent process	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U	kg / fU	1.34E-05
A1-3	Plastics (pp/pvc)	ecoinvent process	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	kg / fU	4.86E-05
B6	Electricity	ecoinvent process	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, U	MJ / fU	4.34E-02
C3	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	2.79E-04
C3	Copper-sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	8.05E-06
C3	Aluminum-sorting	ecoinvent process	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U	kg / fU	1.34E-05
C3	Plastics (pp/pvc)-incineration	ecoinvent process	Waste polypropylene {CH}| treatment of waste polypropylene, municipal incineration FAE | Cut-off, U	kg / fU	4.86E-05
C4	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	8.37E-06
C4	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.07E-04
C4	Copper to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	2.42E-07
C4	Copper to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	6.86E-06
C4	Aluminum to Landfill	ecoinvent process	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U	kg / fU	4.03E-07
C4	Aluminum to recycling	ecoinvent process	Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, U	kg / fU	1.01E-05

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
B4 (A1-3)	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	4.65E-04
B4 (A1-3)	Copper	ecoinvent process	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	kg / fU	1.34E-05
B4 (A1-3)	Aluminum	ecoinvent process	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U	kg / fU	2.24E-05
B4 (A1-3)	Plastics (pp/pvc)	ecoinvent process	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	kg / fU	8.10E-05
B4 (C3)	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	4.65E-04
B4 (C3)	Copper-sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	1.34E-05
B4 (C3)	Aluminum-sorting	ecoinvent process	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U	kg / fU	2.24E-05
B4 (C3)	Plastics (pp/pvc)-incineration	ecoinvent process	Waste polypropylene {CH}| treatment of waste polypropylene, municipal incineration FAE | Cut-off, U	kg / fU	8.10E-05
B4 (C4)	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.39E-05
B4 (C4)	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.78E-04
B4 (C4)	Copper to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	4.03E-07
B4 (C4)	Copper to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.14E-05
B4 (C4)	Aluminum to Landfill	ecoinvent process	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U	kg / fU	6.71E-07
B4 (C4)	Aluminum to recycling	ecoinvent process	Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, U	kg / fU	1.69E-05

Table 58: Radiant Floor System-Towel Dryer dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	5.94E-05
B6	Electricity	ecoinvent process	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, U	kWh / fU	6.53E-03
C3	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	5.94E-05
C4	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.78E-06
C4	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	2.28E-05
B4 (A1-3)	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	1.49E-04
B4 (C3)	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	1.49E-04
B4 (C4)	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	4.46E-06
B4 (C4)	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	5.69E-05

Table 59: Fancoil System-Towel Dryer dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	6.26E-05
B6	Electricity	ecoinvent process	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, U	kWh / fU	6.88E-03
C3	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	6.26E-05
C4	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.88E-06
C4	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	2.40E-05
B4 (A1-3)	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	1.57E-04
B4 (C3)	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	1.57E-04
B4 (C4)	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	4.70E-06
B4 (C4)	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	5.99E-05

Table 60: Radiator System-Total Distribution Pipes dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	(PEX) Crosslinked polyethylene	ecoinvent process	Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate | Cut-off, U	kg / fU	6.27E-05
A1-3	Aluminum	ecoinvent process	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U	kg / fU	2.31E-05
A1-3	insulation - Expanded polyethylene (PE-LD) foam insulation	ecoinvent process	Polyethylene, linear low density, granulate {RER}| polyethylene production, linear low density, granulate | Cut-off, U	kg / fU	1.87E-05
C3	(PEX) Crosslinked polyethylene to incineration	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration FAE | Cut-off, U	kg / fU	9.41E-06
C3	Aluminum-sorting	ecoinvent process	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U	kg / fU	2.31E-05
C3	insulation - Expanded polyethylene (PE-LD) foam insulation to incineration	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration FAE | Cut-off, U	kg / fU	2.81E-06
C4	(PEX) Crosslinked polyethylene to Landfill	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, U	kg / fU	5.33E-05
C4	Aluminum to Landfill	ecoinvent process	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U	kg / fU	2.31E-05
C4	insulation - Expanded polyethylene (PE-LD) foam insulation to Landfill	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, U	kg / fU	1.59E-05

Table 61: Radiant Floor System-Total Distribution Pipes dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	(PEX) Crosslinked polyethylene	ecoinvent process	Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate | Cut-off, U	kg / fU	1.16E-06
A1-3	Aluminum	ecoinvent process	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U	kg / fU	4.28E-07
A1-3	insulation - Expanded polyethylene (PE-LD) foam insulation	ecoinvent process	Polyethylene, linear low density, granulate {RER}| polyethylene production, linear low density, granulate | Cut-off, U	kg / fU	3.46E-07
C3	(PEX) Crosslinked polyethylene to incineration	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration FAE | Cut-off, U	kg / fU	1.74E-07
C3	Aluminum-sorting	ecoinvent process	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U	kg / fU	4.28E-07
C3	insulation - Expanded polyethylene (PE-LD) foam insulation to incineration	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration FAE | Cut-off, U	kg / fU	5.20E-08
C4	(PEX) Crosslinked polyethylene to Landfill	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, U	kg / fU	9.87E-07
C4	Aluminum to Landfill	ecoinvent process	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U	kg / fU	4.28E-07
C4	insulation - Expanded polyethylene (PE-LD) foam insulation to Landfill	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, U	kg / fU	2.95E-07

Table 62: Fancoil System-Total Distribution Pipes dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	(PEX) Crosslinked polyethylene	ecoinvent process	Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate | Cut-off, U	kg / fU	4.92E-05
A1-3	Aluminum	ecoinvent process	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U	kg / fU	1.82E-05
A1-3	insulation - Expanded polyethylene (PE-LD) foam insulation	ecoinvent process	Polyethylene, linear low density, granulate {RER}| polyethylene production, linear low density, granulate | Cut-off, U	kg / fU	1.47E-05
C3	(PEX) Crosslinked polyethylene to incineration	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration FAE | Cut-off, U	kg / fU	7.39E-06
C3	Aluminum-sorting	ecoinvent process	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U	kg / fU	1.82E-05
C3	insulation - Expanded polyethylene (PE-LD) foam insulation to incineration	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration FAE | Cut-off, U	kg / fU	2.20E-06
C4	(PEX) Crosslinked polyethylene to Landfill	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, U	kg / fU	4.19E-05
C4	Aluminum to Landfill	ecoinvent process	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U	kg / fU	1.82E-05
C4	insulation - Expanded polyethylene (PE-LD) foam insulation to Landfill	ecoinvent process	Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, U	kg / fU	1.25E-05

Table 63: Radiator System-Manifold dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	1.86E-06
A1-3	Brass	ecoinvent process	Brass {CH}| market for brass | Cut-off, U	kg / fU	2.39E-05
A1-3	Polymer	ecoinvent process	Polycarbonate {RER}| market for polycarbonate | Cut-off, U	kg / fU	7.97E-07
C3	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	1.86E-06
C3	Brass-sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	2.39E-05
C3	Polymer to incineration	ecoinvent process	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration FAE | Cut-off, U	kg / fU	7.97E-07
C4	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	5.58E-08
C4	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	7.12E-07
C4	Brass to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.20E-06
C4	Brass to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.99E-05
B4 (A1-3)	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	3.10E-06
B4 (A1-3)	Polymer	ecoinvent process	Polycarbonate {RER}| market for polycarbonate | Cut-off, U	kg / fU	1.33E-06
B4 (C3)	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	3.10E-06
B4 (C3)	Polymer to incineration	ecoinvent process	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration FAE | Cut-off, U	kg / fU	1.33E-06
B4 (C4)	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	9.29E-08
B4 (C4)	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.19E-06

Table 64: Radiant Floor System-Manifold dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	1.80E-06
A1-3	Brass	ecoinvent process	Brass {CH}| market for brass | Cut-off, U	kg / fU	2.31E-05
A1-3	Polymer	ecoinvent process	Polycarbonate {RER}| market for polycarbonate | Cut-off, U	kg / fU	7.70E-07
C3	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	1.80E-06
C3	Brass-sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	2.31E-05
C3	Polymer to incineration	ecoinvent process	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration FAE | Cut-off, U	kg / fU	7.70E-07
C4	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	5.39E-08
C4	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	6.88E-07
C4	Brass to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.15E-06
C4	Brass to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.92E-05
B4 (A1-3)	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	2.99E-06
B4 (A1-3)	Polymer	ecoinvent process	Polycarbonate {RER}| market for polycarbonate | Cut-off, U	kg / fU	1.28E-06
B4 (C3)	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	2.99E-06
B4 (C3)	Polymer to incineration	ecoinvent process	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration FAE | Cut-off, U	kg / fU	1.28E-06
B4 (C4)	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	8.98E-08
B4 (C4)	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.15E-06

Table 65: Fancoil System-Manifold dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	1.89E-06
A1-3	Brass	ecoinvent process	Brass {CH}| market for brass | Cut-off, U	kg / fU	2.43E-05
A1-3	Polymer	ecoinvent process	Polycarbonate {RER}| market for polycarbonate | Cut-off, U	kg / fU	8.11E-07
C3	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	1.89E-06
C3	Brass-sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	2.43E-05
C3	Polymer to incineration	ecoinvent process	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration FAE | Cut-off, U	kg / fU	8.11E-07
C4	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	5.68E-08
C4	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	7.24E-07
C4	Brass to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.22E-06
C4	Brass to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	2.03E-05
B4 (A1-3)	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	3.15E-06
B4 (A1-3)	Polymer	ecoinvent process	Polycarbonate {RER}| market for polycarbonate | Cut-off, U	kg / fU	1.35E-06
B4 (C3)	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	3.15E-06
B4 (C3)	Polymer to incineration	ecoinvent process	Waste plastic, mixture {CH}| treatment of waste plastic, mixture, municipal incineration FAE | Cut-off, U	kg / fU	1.35E-06
B4 (C4)	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	9.46E-08
B4 (C4)	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.21E-06

Table 66: Radiator System-Boiler dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	2.69E-04
A1-3	Copper	ecoinvent process	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	kg / fU	3.84E-05
A1-3	Aluminum	ecoinvent process	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U	kg / fU	4.61E-05
A1-3	Plastics (pp/pvc)	ecoinvent process	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	kg / fU	3.07E-05
B6	Natural gas	ecoinvent process	Natural gas, low pressure {IT}| market for natural gas, low pressure | Cut-off, U	MJ / fU	4.00E+00
C3	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	2.69E-04
C3	Copper-sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	3.84E-05
C3	Aluminum-sorting	ecoinvent process	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U	kg / fU	4.61E-05
C3	Plastics (pp/pvc)-incineration	ecoinvent process	Waste polypropylene {CH}| treatment of waste polypropylene, municipal incineration FAE | Cut-off, U	kg / fU	3.07E-05
C4	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	8.06E-06
C4	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.03E-04
C4	Copper to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.15E-06
C4	Copper to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	3.27E-05
C4	Aluminum to Landfill	ecoinvent process	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U	kg / fU	1.38E-06
C4	Aluminum to recycling	ecoinvent process	Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, U	kg / fU	3.48E-05

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
B4 (A1-3)	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	4.48E-04
B4 (A1-3)	Copper	ecoinvent process	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	kg / fU	6.40E-05
B4 (A1-3)	Aluminum	ecoinvent process	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U	kg / fU	7.68E-05
B4 (A1-3)	Plastics (pp/pvc)	ecoinvent process	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	kg / fU	5.12E-05
B4 (C3)	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	4.48E-04
B4 (C3)	Copper-sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	6.40E-05
B4 (C3)	Aluminum-sorting	ecoinvent process	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U	kg / fU	7.68E-05
B4 (C3)	Plastics (pp/pvc)-incineration	ecoinvent process	Waste polypropylene {CH}| treatment of waste polypropylene, municipal incineration FAE | Cut-off, U	kg / fU	5.12E-05
B4 (C4)	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.34E-05
B4 (C4)	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.72E-04
B4 (C4)	Copper to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.92E-06
B4 (C4)	Copper to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	5.46E-05
B4 (C4)	Aluminum to Landfill	ecoinvent process	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U	kg / fU	2.30E-06
B4 (C4)	Aluminum to recycling	ecoinvent process	Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, U	kg / fU	5.80E-05

Table 67: Radiant Floor System-Boiler dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	2.60E-04
A1-3	Copper	ecoinvent process	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	kg / fU	3.71E-05
A1-3	Aluminum	ecoinvent process	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U	kg / fU	4.45E-05
A1-3	Plastics (pp/pvc)	ecoinvent process	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	kg / fU	2.97E-05
B6	Natural gas	ecoinvent process	Natural gas, low pressure {IT}| market for natural gas, low pressure | Cut-off, U	MJ / fU	3.76E+00
C3	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	2.60E-04
C3	Copper-sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	3.71E-05
C3	Aluminum-sorting	ecoinvent process	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U	kg / fU	4.45E-05
C3	Plastics (pp/pvc)-incineration	ecoinvent process	Waste polypropylene {CH}| treatment of waste polypropylene, municipal incineration FAE | Cut-off, U	kg / fU	2.97E-05
C4	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	7.79E-06
C4	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	9.94E-05
C4	Copper to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.11E-06
C4	Copper to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	3.16E-05
C4	Aluminum to Landfill	ecoinvent process	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U	kg / fU	1.34E-06
C4	Aluminum to recycling	ecoinvent process	Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, U	kg / fU	3.36E-05

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
B4 (A1-3)	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	4.33E-04
B4 (A1-3)	Copper	ecoinvent process	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	kg / fU	6.19E-05
B4 (A1-3)	Aluminum	ecoinvent process	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U	kg / fU	7.42E-05
B4 (A1-3)	Plastics (pp/pvc)	ecoinvent process	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	kg / fU	4.95E-05
B4 (C3)	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	4.33E-04
B4 (C3)	Copper-sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	6.19E-05
B4 (C3)	Aluminum-sorting	ecoinvent process	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U	kg / fU	7.42E-05
B4 (C3)	Plastics (pp/pvc)-incineration	ecoinvent process	Waste polypropylene {CH}| treatment of waste polypropylene, municipal incineration FAE | Cut-off, U	kg / fU	4.95E-05
B4 (C4)	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.30E-05
B4 (C4)	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.66E-04
B4 (C4)	Copper to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.86E-06
B4 (C4)	Copper to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	5.27E-05
B4 (C4)	Aluminum to Landfill	ecoinvent process	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U	kg / fU	2.23E-06
B4 (C4)	Aluminum to recycling	ecoinvent process	Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, U	kg / fU	5.60E-05

Table 68: Fancoil System-Boiler dataset in SimaPro

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
A1-3	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	2.74E-04
A1-3	Copper	ecoinvent process	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	kg / fU	3.91E-05
A1-3	Aluminum	ecoinvent process	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U	kg / fU	4.69E-05
A1-3	Plastics (pp/pvc)	ecoinvent process	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	kg / fU	3.13E-05
B6	Natural gas	ecoinvent process	Natural gas, low pressure {IT}| market for natural gas, low pressure | Cut-off, U	MJ / fU	3.89E+00
C3	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	2.74E-04
C3	Copper-sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	3.91E-05
C3	Aluminum-sorting	ecoinvent process	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U	kg / fU	4.69E-05
C3	Plastics (pp/pvc)-incineration	ecoinvent process	Waste polypropylene {CH}| treatment of waste polypropylene, municipal incineration FAE | Cut-off, U	kg / fU	3.13E-05
C4	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	8.21E-06
C4	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.05E-04
C4	Copper to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.17E-06
C4	Copper to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	3.33E-05
C4	Aluminum to Landfill	ecoinvent process	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U	kg / fU	1.41E-06
C4	Aluminum to recycling	ecoinvent process	Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, U	kg / fU	3.54E-05

Module	Item	ecoinvent process or elementary flow	Name of the activity in SimaPro	Unit	Quantity
B4 (A1-3)	Steel	ecoinvent process	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg / fU	4.56E-04
B4 (A1-3)	Copper	ecoinvent process	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	kg / fU	6.52E-05
B4 (A1-3)	Aluminum	ecoinvent process	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, U	kg / fU	7.82E-05
B4 (A1-3)	Plastics (pp/pvc)	ecoinvent process	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	kg / fU	5.21E-05
B4 (C3)	Steel- sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	4.56E-04
B4 (C3)	Copper-sorting	ecoinvent process	Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U	kg / fU	6.52E-05
B4 (C3)	Aluminum-sorting	ecoinvent process	Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U	kg / fU	7.82E-05
B4 (C3)	Plastics (pp/pvc)-incineration	ecoinvent process	Waste polypropylene {CH}| treatment of waste polypropylene, municipal incineration FAE | Cut-off, U	kg / fU	5.21E-05
B4 (C4)	Steel to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	1.37E-05
B4 (C4)	Steel to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	1.75E-04
B4 (C4)	Copper to Landfill	ecoinvent process	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, U	kg / fU	6.52E-05
B4 (C4)	Copper to recycling	ecoinvent process	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U	kg / fU	5.56E-05
B4 (C4)	Aluminum to Landfill	ecoinvent process	Waste aluminium {CH}| treatment of waste aluminium, sanitary landfill | Cut-off, U	kg / fU	2.35E-06
B4 (C4)	Aluminum to recycling	ecoinvent process	Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, U	kg / fU	5.90E-05