Comparative Analysis of the Environmental Impact of Individual and Collective Heating Systems Based on LCA

Lau Leman

Thesis submitted for the degree of
Master of Science in Engineering:
Energy

Thesis supervisors:
Prof.dr.ir. Lieve Helsen
Dr.ir-arch. Damien Trigaux

Assessors:
Prof.dr.ir. Johan Meyers
Dr.ir.-arch. Els Van De Moortel

Mentors:
Ir. Lucas Verleyen
Ir. Naomi Adam

Academic year 2023 – 2024

© Copyright KU Leuven

Without written permission of the thesis supervisors and the author it is forbidden to reproduce or adapt in any form or by any means any part of this publication. Requests for obtaining the right to reproduce or utilize parts of this publication should be addressed to Faculteit Ingenieurswetenschappen, Kasteelpark Arenberg 1 bus 2200, B-3001 Heverlee, +32-16-321350.

A written permission of the thesis supervisors is also required to use the methods, products, schematics and programmes described in this work for industrial or commercial use, and for submitting this publication in scientific contests.

Preface

Met het indienen van mijn thesis loopt mijn eerste academische periode bijna ten einde. Gelukkig kan ik nog een jaartje in Leuven blijven voor de Manama AI. De afgelopen vijf jaar in Leuven hebben niet alleen mijn kennis en technische vaardigheden uitgebreid, maar ook mijn soft skills en sociale vaardigheden enorm doen groeien. Hiervoor wil ik graag een aantal mensen bedanken.

Allereerst een welgemeend dankjewel aan mijn begeleiders Lucas en Naomi, wiens aanstekelijke enthousiasme mijn motivatie altijd hoog hield en daarmee zeker hebben bijgedragen aan dit fantastische eindresultaat. Naast mijn begeleiders wil ik ook graag mijn promotor Damien Trigaux bedanken, die eveneens als begeleider optrad. Hij heeft me enorm geholpen met het doorworstelen van de LCA-methode en het onder de knie krijgen van de Totem-tool en de MMG KU Leuven-tool. Ook een bedankje aan mijn promotor Lieve Helsen, voor haar kritische vragen en opmerkingen en die op het juiste pad gefocust hielden. Tijdens het zoekproces, mocht ik ook profiteren van een boeiend bedrijfsbezoek aan Mirom en een interessante presentatie van Boringen Verheyden. Hun technische kennis van het domein bood dat extra inzicht dat de gaatjes in her eerder theoretische denkkader kon vullen.

Verder, wil ik nog een aantal mensen bedanken die me nauw aan het hart liggen. De voorbije vijf jaar heb ik het geluk gehad om mijn tijd te kunnen doorbrengen in het gezelligste kot van Leuven. De kotreisjes en soms een beetje losbandige middagpauzes tijdens de examen periode zal ik nooit vergeten. De iconische alma maaltijdjes met Kamiel, Rik, Dries, Capser, iedere week aangevuld met onvergetelijke (nachtelijke) avonturen. Naast de vrienden in Leuven kon ik in Lier ook altijd rekenen op de 'atletiek squad' zoals we ons vroeger altijd noemden, voor de nieuwjaarsavonden en de reisjes in de zomer vakantie. En dan uiteraard mijn bijna-broer Djeupe en broer Beertje, die mij gemotiveerd hielde om te blijven lopen en mij bezig hielden met stomme vragen als ik weer niks te doen had. Om het rijtje af te sluiten, nog een dikke merci naar mijn ouders om mij al deze kansen te geven om mezelf te ontwikkelen en al deze momenten te mogen meemaken. Zonder hen was dit alles behalve mogelijk geweest.

Dan wil ik om af te sluiten ook de jury nog bedanken om de tijd te nemen om deze thesis te lezen en te beoordelen, ik hoop dat jullie het interessant vinden.

Lau Leman

Contents

Abstract

The building sector's significant environmental impact necessitates improvements in material and energy use. This thesis compares the environmental impacts of various individual heating systems and one collective heating system, using 'De Schipjes' as use case, to assess whether collective systems can reduce environmental impact. The Life Cycle Asessment (LCA) method was selected as the most suitable tool for this analysis. The study utilizes the MMG KU Leuven tool, based on the MMG LCA method, to facilitate district-level assessment. A literature review of heating system components and their material composition was conducted to integrate the necessary elements for the models.

Once the LCA method was established and the heating systems analyzed, the different scenarios were modeled. First, buildings were modeled using data from previous studies, supplemented by reference scenarios from the Totem tool where information was missing. Next, the heating systems were modeled. Five individual scenarios and one collective scenario were considered. Energy use was estimated for each scenario using the equivalent hour degree days method and a dynamic simulation using rule-based control.

After modelling the scenarios, their environmental impacts can be analyzed. Depending on the energy calculation method, either the individual scenario with a gas boiler or GSHP performed best, closely followed by the collective scenario, which showed great potential, particularly given the possibility for further improvements. Also, for heat pumps in general there is still room for improvement, regarding the high impact of the material use. Across all scenarios, the depletion of fossil fuels and climate change were the primary contributors to the environmental impact. However, only considering operational CO_2 emissions, instead of an LCA-based approach, leads to a big underestimation of the impact and different conclusions.

In a sensitivity analysis, the impact of different HP models was compared, highlighting the importance of the used LCA data and HP model. Also different refrigerants were analyzed, with CO_2 coming out on top. Aside from environmental impact, other, thermophysical and chemical properties should be considered as well. Finally, the effect of the electricity mix was examined. Integrating more renewable energy sources, particularly wind energy, could substantially improve the current electricity mix by lowering its environmental impact. Furthermore, the use of static energy calculations slightly underestimates the impact of electricity use compared to a dynamic analysis.

List of Figures

List of Tables

List of Abbreviations and Symbols

Abbreviations

EU	European Union
LCA	Life Cycle Assessment
HS	Heating System
PEF	Product Environmental Footprint
CCUS	Carbon Capture, Use and Storage
MMG	Milieugerelateerde Materiaalprestatie van Gebouwelementen
TOTEM	Tool to Optimise the Total Environmental impact of Materials (Environmental performance of building elements)
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCC	Life Cycle Costing
E-LCA	Environmental-Life Cycle Assessment
MCA	Multi Criteria Assessment
CEN	European Committee for Standardisation
ILCD	International Life Cycle Data system
PUR	Polyurethane
DHN	District Heating Network
ASHP	Air Source Heat Pump
GSHP	Ground Source Heat Pump
GDHN	Generation District Heating Network
COP	Coefficient Of Performance
CHP	Combined Heat and Power
HDPE	High Density PolyEthylene
PP	PolyPropylene
FRP	Fiberglass-Reinforced Plastics
PE	PolyEthylene
HCF	Heat Carrier Fluid
CFC	ChloroFluoroCarbons
ODP	Ozone Depletion Potential
GWP	Global Warming Potential
PUR	PolyURethane
HE	Heat Exchanger
PB	PolyButylene

DPHE	Double Pipe Heat Exchanger
STHE	Shell and Tube Heat Exchanger
CTHE	Coiled Tube Heat Exchanger
ETHE	Enhanced Tube Heat Exchanger
PHE	Plate Heat Exchanger
PCM	Phase Changing Materials
VIP	Vacuum Insulated Panels
DHW	Domestic Hot Water
PEX	cross-linked PolyEthylene
Al	Aluminum
CPVC	Chlorinated PolyVinyl Chloride
HVAC	Heating Ventilation and Air Conditioning
OPMV	Occupied zone Predictive Mean Vote
STC	Solar Thermal Collector
WT	Water Tank
V	valve
OD	Outer diameter
t	Thickness
RH	Relative Humidity
EHDD	Equivalent Heating Degree Days
RBC	Rule-Based Control

Symbols

E_{CH}	Energy use for central heating [MJ]
U_m	Average heat transfer Coefficient $[W/m^2K]$
S	Surface $[m^2]$
V	Heated volume $[m^3]$
n_{vent}	Ventilation $[h^{-1}]$
n_{inf}	Infiltration $[h^{-1}]$
n_{tot}	sum of the venilation and infiltation $[h^{-1}]$
DD_{eq}	Equivalent degree-days [°s]
η_d	Efficiency of the distribution system[-]
η_e	Efficiency of the emission system[-]
η_c	Efficency of the system control [-]
E_{DHW}	Energy use for domestic hot water [MJ]
C_{HW}	Domestic hot water use [l/person/day]
T_{HW}	Temperature of the hot water [°C]
T_{CW}	Temperature of the hot water [°C]
N	Number of residents [-]
$Q_{storage\ loss}$	Yearly storage loss of the domestic hot water [MJ]
E_{op}	Total operational energy use [MJ]
$P_{col,col}$	Total power of the collective system
$\dot{Q}_{gshp}$	Heat generated by the GSHP [W]
COP_{gshp}	Coefficien of performance of the GSHP [-]

$P_{pump,bf}$	Power of the circulation pump in the bore field of the collective GSHP [W]
$P_{pump,gshp}$	Power of the circulation pump on the secondary side of the collective GSHP [W]
$P_{pump,stc}$	Power of the circulation pump from the STC [W]
$P_{pump,distr}$	Power of the circulation pump in the collective distribution network [W]
$P_{col,ind}$	Total power of the individual part form the collective scenario [W]
$\dot{Q}_{bhp}$	Generated heat by the BHP [W]
COP_{bhp}	Coefficient of performance of the BHP
$P_{pump,bhp}$	Power of the circulation pump at the primary side of the BHP [W]
$E_{tot,col}$	Electricity use of the collective scenario per UFA [MJ]
$Q_{tot,ind}$	Total generated heat in de individual scenarios [MJ]
$\dot{Q}_{stc}$	Heat generation by the STC [W]
$\dot{Q}_{col,loss}$	Heat loss in the collective distribution network [W]
$E_{gas\ boiler}$	Electricity use of the individual scenario with a gas boiler per UFA[MJ]
$E_{electric\ heating}$	Total electricity use of the individual scenario with electric heating [MJ]
E_{ashp}	Total electricity use of the individual scenario with an ASHP[MJ]
E_{gshp}	Total electricity use of the individual scenario with a GSHP[MJ]

Chapter 1

Introduction

1.1 Problem Statement

As global warming and scarcity of resources keep increasing, there is a trend towards more sustainability. A concerning contributor to this global warming is the energy sector, which entails all the activities of the production, sale, distribution and emission of energy. The construction sector is highly resource-intensive, with roughly 50% of Europe's processed raw materials allocated to construction activities. Furthermore, approximately 30% of generated waste is attributed to construction and demolition processes [18]. In terms of environmental impact, buildings contribute significantly, accounting for over 40% of the world's primary energy demand, thereby emitting one-third of the global greenhouse gases [19]. *Eurostat* reports that half of the energy, used in the European Union is attributed to space heating and cooling, with 70% of this energy still originating from fossil fuels. Specifically in the residential sector, 80% of energy is utilized for space heating and domestic hot water [20]. To reach their climate goals in the building sector, the EU has implemented standards to reduce its primary energy demand for heating [21]. There are also more initiatives to address global warming on a global scale via e.g., the Kyoto Protocol and the Paris Agreement. However, their effectiveness is compromised by a lack of enforceability and the potential for free-riding. In the EU, this primary energy demand for heat can be reduced, by lowering the heat demand or by increasing the efficiency of the heat production. The heat demand can be reduced, by increasing the insulation and air tightness and by relaxing the comfort level. The efficiency of heat production can be improved by replacing gas boilers with heat pumps or by installing solar thermal collectors that can provide part of the heat in a renewable manner. The combination of the electrification of the heating sector, with green electricity production, shows great potential to reduce climate change. However, next to reducing the required energy demand and energy source, these heat pump installations are more material intensive, requiring a refrigerant and in some cases a bore field. Apart from changing the primary energy source, a possible increase in efficiency can be achieved, by shifting from individual towards collective heating systems.

In this study, the sustainability of collective and individual heating systems is assessed. According to Santander [22], "Sustainability consists of fulfilling the needs of current generations without compromising the needs of future generations, while ensuring a balance between economic growth, environmental care, and social well-being". Environmental sustainability focuses on preserving biodiversity and limiting climate impact, without interfering too much with social and economic progress. Apart from environmental, there is also economic and social sustainability, where the focus lies on making profits and, social stability and cohesion respectively. This thesis mainly focuses on the environmental sustainability of heating systems. To make the energy sector more sustainable, a shift towards more efficient technologies and renewable sources should be made. If this is combined with carbon capture utilization and storage (CCUS), the environmental impact of energy production can be reduced significantly [23].

In this study, the environmental impact of several individual heating systems and one collective heating system is analyzed and compared to assess whether a transition towards collective heating systems is desirable. It is important to note that, apart from environmental considerations, economic and comfort factors are often the determining factors in choosing a heating system. However, the emphasis of this study is on the environmental impact.

Regarding environmental damages, greenhouse gas emissions, and therefore global warming, are not the only concerns. Typically, only the operational CO_2 emissions are taken into account when assessing environmental impact. However, to comprehensively evaluate the total environmental impact, it is essential to consider not only the CO_2 emissions during operation but the total impact of energy use and materials over the entire life cycle. Apart from operational CO_2, other indicators such as land use, particulate matter, ionizing radiation, depletion resources, water depletion, etc., should be incorporated as well [15]. Further, the impact of the various indicators have to be determined over the system's entire life. Therefore, the total environmental impact of one collective and several individual heating systems is determined, with the aim of gaining a comprehensive understanding of the environmental implications of the different components across all life cycle phases. To estimate the total environmental impact, the MMG KU Leuven tool will be utilized. This tool enables the analysis of the environmental impact of buildings and districts by applying a Life Cycle Assessment (LCA) methodology. However, it currently lacks the capability to analyze collective heating systems. A literature review will be conducted to integrate this functionality into the tool, enabling the analysis and comparison of the environmental impact of collective heating systems.

To evaluate the potential of collective heating systems, the environmental impact of the collective heating system in the social housing district 'De Schipjes' in Bruges will be assessed. This assessment will be compared to several scenarios featuring individual heating systems, including those utilizing gas boilers, electric heating, and various types of heat pumps.

1.2 Research Questions

The environmental impact of the different scenarios will be analyzed from two main perspectives: environmental impact indicators and life cycle phases. To facilitate this assessment, several research questions have been formulated below.

How do the different individual scenarios compare regarding their environmental impact? Are collective heating systems more sustainable than individual heating systems, regarding environmental impact?

The first research question aims to address the primary objective of this thesis: identifying the heating system with the lowest environmental impact. To achieve this goal, a comparative analysis will be undertaken, including various heating systems. The comparative analysis will begin with an evaluation of individual heating systems, followed by a comparison between individual and collective scenarios. Each system will be developed based on a specific use case, as detailed in section 3.1. The comparison will rely on a Life Cycle Assessment (LCA).

How is the environmental impact distributed across the components?

In the modeling of the different scenarios, various assumptions will need to be made, regarding the modelling of the different components e.g., different heat pump models, material selection, etc. Depending on the impact of each component, these assumptions may have either a considerable or a negligible impact on the outcome.

Does an assessment based on climate change lead to a different conclusion than one based on an LCA, including various impact indicators? How is the impact distributed across all these indicators?

Typically, the impact on the climate is used to determine the environmental impact of systems. In an LCA on the other hand, more than just climate change ($CO_2eq.$ emissions) is considered, by including more impact indicators. Additionally, the LCA does not only take the operational phase into account, but the entire cradle-to-grave sequence. The impact of climate change will be compared to the total impact by aggregating over all indicators. This will demonstrate the extent to which the current focus on climate change underestimates the actual environmental impact of systems. Furthermore, different conclusions may be drawn from both approaches regarding which system has the lower environmental impact.

What is the contribution of the different life cycle phases (production, construction, operation, end of life) to the total environmental impact? How does this differ between an individual system and a collective system?

In an LCA, the assessment is divided into multiple phases. The environmental impact of these phases depends on factors such as the type and quantity of materials used, processing activities, transportation, energy consumption, etc., all of which are specific to each scenario. For instance, the production and construction of a ground source heat pump with a bore field typically require significantly more materials and labor compared to a gas boiler. However, the energy source is different and the operational energy use of the heat pump is usually lower.

1.3 Outline

This thesis will commence with a literature review, aimed at gaining a deeper understanding of the topic, validating existing research, and identifying areas that require further investigation. The literature study will encompass an examination of LCA methodologies, followed by a comprehensive discussion on individual and collective heating systems.

In the methodology section, a detailed description of the use case will be provided, followed by an explanation of how the different scenarios will be modeled. Initially, the building decomposition will be determined, followed by the selection and modeling of heating systems. The methodology will be completed with a discussion on methods for determining operational energy use.

Once the different scenarios have been modeled and the energy use has been estimated, their environmental impact will be assessed using two different energy calculation methods. Following a thorough discussion of the results, a sensitivity analysis will be conducted to validate critical assumptions and broaden the scope of the study. Finally, the thesis will conclude by addressing the research questions and providing recommendations for future research.

Chapter 2

Literature Review

This section summarizes all the information and data on this topic that is already present and reveals the gaps in the literature that have to be filled in. Many studies have already analyzed the performance and environmental impact of the individual heating systems, but analyses of collective heating systems seem scarce. This literature review will commence with a comparative analysis of various LCA methodologies will be conducted to determine the most suitable approach for the study, followed by a concise overview of the selected LCA methodology. Regarding the heating systems, first a discussion on heating systems in general will be provided. Following this, existing studies of technical installations and individual heating systems will be reviewed, determining all the components and their material decompositions. This will be succeeded, by an extensive analysis of collective heating systems.

2.1 Life Cycle Assessment Tool

To determine the total impact of a system on the environment, more than only the greenhouse gasses have to be considered. Multiple assessment methods exist to determine the sustainability of a system. They can be subdivided into two main categories: life cycle assessment (LCA) tools and scoring tools. The main differences between both tools are discussed in the paper of Damien T. [15] and are summarized below.

2.1.1 Tool Comparison and Selection

Scoring tools are rather used for labelling, as they concentrate on calculating an aggregated sustainability score. LCA tools lean more towards analysis and design, as they provide quantitative environmental impact data to aid decision-making. Concerning the scale coverage, scoring tools are mostly related to medium and large-scale developments. Whereas, the applicability of LCA tools ranges from small to large-scale levels. The tools also vary in their evaluation structures. LCA tools employ a detailed modelling approach, subdividing into components and elements, and employing hierarchical scale levels within the neighborhood. In contrast, scoring tools do not necessitate a modelling step; their evaluation relies on a breakdown into thematic categories, each encompassing a subset of criteria.

Scoring tools encompass a wider range of sustainability parameters, including environmental as well as comfort and social factors and use quantitative as well as qualitative indicators.

Conversely, LCA tools are confined to evaluating the environmental dimension, only based on quantitative indicators, concentrating on global and regional environmental impacts. Local impacts such as pollution and disturbances are either not or only partially considered. Scoring tools typically derive an overall score by assigning weights to different indicators. LCA tools, on the other hand, do not always aggregate the results into one score, allowing a more detailed analysis [15].

In this thesis, the emphasis is placed on assessing the environmental impact of heating systems, making an LCA tool well-suited for this purpose. Such a tool allows for a more precise and layered evaluation of the environmental impact of each component in the system throughout all stages of its life cycle. Depending on the utilized LCA tool, different indicators are taken into account. The LCA method used in this study is based on the MMG KU Leuven tool. This modular spreadsheet tool is an extension of the TOTEM tool, originally developed to assess the environmental impact of buildings in the Flanders region. The MMG KU Leuven method goes a step further, enabling analysis at the district level. However, it currently lacks the capability to analyze collective heating systems. Therefore, a comprehensive analysis of various heating systems is conducted to incorporate this possibility.

2.1.2 LCA Procedure

Generally, a Life Cycle Assessment (LCA), comprises four distinct stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [24]. The initial phase, goal and scope definition, serves as the foundational step, wherein the objectives and parameters of the assessment are established. The 'goal' aspect describes the aim of the analysis, elucidating the scenario and rationale driving the assessment. The 'scope' component entails outlining the system, defining its boundaries, and specifying the functional unit for the LCA analysis.

In a second step, the inventory analysis (LCI) is made. In this step, the material flows associated to each element in the system are identified. The input consists of all the flows from nature to the system from cradle to grave, such as raw materials. The output describes all the flows from the system to the environment, e.g. emissions. The reliability and accuracy of data, utilized in this phase are pivotal for the correctness of the subsequent LCA stages.

In a third step, the data gathered in the LCI step is translated into an environmental impact. This impact analysis consists of several sub-steps. First, the relevant impact indicators are selected. This is followed by the classification, in which the data of the LCI is assigned to these different indicators.

In the fourth and last step, the results from the LCA are interpreted. The results are connected to the framework, established during the initial goal and scope definition phase. The completeness, sensitivity and consistency of the selected methodology and the results are discussed. For this purpose, often a sensitivity analysis is performed. Additionally, the results are often compared to findings in previous studies.

2.2 Heating Systems

Heating systems usually consist of three parts: heat generation, heat distribution and heat emission. To assess the total environmental impact of heating systems, not only the energy use, but also material use is important. Determining the components used in the different heating systems and their material decomposition is therefore essential. Currently, the majority of buildings buildings utilize individual heating systems, with each their own heat generation unit, which is often a gas boiler. These individual generation units seem to have a substantial environmental impact, as will be discussed further. If all these individual heat generation units could be replaced by one central unit, the environmental impact could be divided over all its users, potentially reducing the overall environmental impact.

First, individual heating systems are discussed, followed by an detailed examination of collective heating systems. The collective heating system will be analyzed by breaking it down into heat generation units, the distribution network, and the emission units. Each component will be discussed in more detail after a brief introduction to collective heating systems.

2.2.1 Individual Heating Systems

In most buildings, the heat is generated by a gas boiler, distributed via pipes and emitted through radiators. In newer buildings, heat pumps are being installed more often, paired with floor heating for efficient heat distribution and emission. Two main types of heat pumps can be distinguished: air-source heat pumps (ASHPs) and water- or ground-source heat pumps (GSHPs). ASHPs utilize the outside air to extract heat or cold, with performance varying based on the outside temperatures. GSHPs on the other hand, are much more complex but have a higher efficiency. They tap into shallow geothermal energy through horizontal or vertical bore fields, at depths from several up to two hundred meters and can operate in open- or closed-loop configurations. Due to the higher stability of the ground temperature, GSHPs typically exhibit a higher performance. Further elaboration on these GSHPs will be provided for the collective heating system. Notably, heat pumps operate at lower temperatures and use electricity instead of natural gas, to upgrade the available heat.

A study performed by Haoding Lin et al. [25], compared the performance of condensing gas boilers and hybrid heat pumps in the UK. The results show a lower environmental impact from the hybrid heat pump for most indicators of the LCA analysis (see section 2.1 on LCA), with a remarkable reduction of greenhouse gas emissions and fossil fuel depletion up to 48% compared to the condensing gas boiler. A sensitivity analysis of the electricity mix showed large variations in the environmental impact of the heat pump, caused by its large operational electricity use. Due to their lower operating temperatures, heat pumps are typically integrated with floor heating systems, resulting in higher efficiencies and improved cycling of the heat pump. Floor heating is often supplemented by radiators, which provide greater heating flexibility due to their higher heating rates. The benefits of combining floor heating with heat pumps are examined in a study by Loan Sarbu et al. [26]. However, these advantages generally apply when considering only system efficiency. To satisfy comfort criteria, floor heating is often combined with radiators.

Ali H.-F. et al. [27] compared the energy efficiency, cost, and relative payback period of air source heat pumps (ASHPs) and ground source heat pumps (GSHPs) over a ten-year lifetime. The study found that ASHPs have a shorter payback period compared to GSHPs.

In a subsequent study by A.C. Voilante et al. [1], a comparative life cycle assessment (LCA) of ground source and air source heat pumps was conducted. Multiple indicators were evaluated over the entire cradle-to-grave cycle. The ASHPs exhibited a slightly higher operational impact due to a lower coefficient of performance (COP), resulting in increased operational energy use. The initial impacts during the production and construction phases were higher for the GSHP. However, since the lifetime of the bore field for the GSHP was considered to be one hundred years, its effect on the system's overall environmental impact was minimal. Consequently, the scenario with a GSHP demonstrated a smaller long-term environmental impact.

Typically, gas boilers exhibit a smaller environmental footprint in their production phase compared to heat pumps. Similarly, air-source heat pumps (ASHPs) demonstrate a lower environmental impact during production than ground-source heat pumps (GSHPs). However, when considering the environmental impact during the usage phase, the order of impact is reversed. Later in this study, various individual scenarios employing these different types of technical installations will be compared alongside a collective heating scenario.

2.2.2 Collective Heating Systems

District Heating Network Types

If the individual heat generation units within buildings are replaced by one or more central, shared heat sources, it is typically referred to as a collective heating system or district heating system. These district heating systems or networks (DHNs) have already been implemented since the nineteenth century in the US and have made a lot of progress since. Initially, the heat was generated in a coal-fired power plant and transported through concrete ducts at high temperatures and low pressure, using steam as heat carrier. Later, around 1930, these systems were replaced by the second generation networks, using pressurized hot water as heat carrier, with temperatures slightly over $100°C$. The risk of steam explosions was removed and heat losses were reduced. Also, combined heat and power (CHP) was introduced, saving primary energy use by combining electricity and heat production. However, the network lacked proper control and heat losses were still substantial. Until now, fossil fuels were the main primary heat source. After the oil crisis in the 1970s, this oil was replaced by cheaper and/or more renewable sources such as biomass and residual heat. Sometimes even geothermal and solar thermal sources were used as supplements. In these third-generation DHNs, the heat was transported through prefabricated and pre-insulated pipes, instead of concrete ducts, at temperatures below $100°C$. This insulation and lower distribution temperature significantly reduced the heat loss [28].

Certain studies, exemplified by Jacopo F. et al. [29], explore the feasibility of modern DHNs, providing space heating and domestic hot water (DHW). These systems entail one or more central heat sources and a heating network that transports heat from the source to buildings. Each building retains its internal heat distribution network, potentially aided by a booster unit to elevate heat temperatures if necessary. The 3rd generation district heating network (DHN), examined in their study, appears to have a higher environmental impact than the individual system with a heat pump. But, despite the higher impact, it definitely showed potential. They recommended that new designs of existing third-generation DHNs or the implementation of fourth-generation DHNs should be topics of future research, to make DHNs more competitive.

The book from Frederiksen et al. [30], describes the opportunities for reducing the environmental impact through the integration of collective heating systems: more potential for renewable sources, scaling advantages, potential for higher generation efficiencies, multi-use cases, etc. However, a significant drawback lies in the heat loss during distribution from the central heat generation site to the heat emission site. Conversely, district heating and cooling can provide energy savings, which lead on itself to lower emissions. For example, excess heat from industries can be recovered, replacing boilers running on fossil fuels. However, while optimizing the heat generation side, the distribution and emission side should not be left out. Some contend that rather than investing in district heating networks, the buildings could be retrofitted towards zero energy houses, eliminating emissions from heating. This however would be very costly. The integration of District Heating Networks (DHNs) enables the use of renewable energy sources such as solar energy, geothermal energy, biomass fuels, and wind energy as primary sources for heat generation. Apart from economic benefits, Larger-scale operations are monitored more closely and allow emissions to be treated centrally, at the source. Furthermore, in central combustion units, burnt fuels are selected more carefully to minimize damages. Individuals, on the other hand, might use wet wood or other highly emitting fuels, potentially causing more harm to their surroundings by emitting toxic particles. Moreover, when the emitted particles are captured in a central unit, they can sometimes be repurposed, such as in the production of materials like gypsum.

Currently, mainly fourth-generation DHNs are being employed. They integrate a wide variety of renewable heat sources. The supply temperature of the DHN is below $70°C$, lowering the grid losses. The simple control is replaced by a smart control, trying to integrate the heating network into a smart energy system, e.i. combining smart heat, cold, electricity, and gas grids. The lower supply temperatures present an opportunity to integrate heat pumps. With only a small energy input, they can upgrade the lower temperature heat for domestic hot water and space heating [28] [31]. While the fourth-generation DHNs are still improving, recent studies investigate the potential of a new type of DHN. This potential fifth generation of DHNs would operate at even lower temperatures, close to the ground temperature, almost eliminating the heat losses. 5GDHNs are defined by Henrik L. et al. [32] as "DH networks operating at near-ground temperatures using a bidirectional exchange of heat and cold between connected buildings, facilitated by seasonal storage". The heating network consists of many producers, prosumers and consumers, that are all connected via the network, leading to heavily distributed generation and consumption. All the players, such as offices, stores, residences, industries, etc., either use or supply heat and supply or use cold. Again, heat pumps are required to reach proper temperatures for domestic hot water. Due to the low supply temperatures, the heat pump should be combined with floor heating, possibly aided by radiators or electric heating. That way a very high coefficient of performance (COP) can be achieved.

The collective heating system in this study is considered to be a 4GDHN. Rasmus Lund et al. [33] and A.M. Jodeiri et al. [34], investigate the potential of different heat sources in a district heating network, such as process heat from industries, sewers and landfills, solar thermal, geothermal, biomass, etc. The potential of the different sources depends on certain factors such as logistics, availability, demand, etc. Eventually, the selection is based on optimization of both environmental impact and cost efficiency.

After generation, the heat can be conveyed directly to the network or indirectly via heat exchangers, particularly when different heat transfer fluids are utilized. Subsequently, the fluid is transported through the piping network using circulation pumps and control valves. Each building is equipped with a heat exchanger, to transfer the heat into the internal heating network. Often a booster heat pump is employed as well, to elevate the temperature for domestic hot water. In both collective and individual heating systems, different types of heat pumps can be employed (ASHP or GSHP). Apart from a heat exchanger (HE) and a Booster heat pump (BHP) for DWH, the building's internal heating systems are similar to the individual heat pump-based heating systems, combining floor heating and radiators.

Heat Sources

The different heat sources will be discussed one by one. In heavily industrialized regions, there is a significant potential for utilizing process heat. H. Kristina et al. [35] investigate the economic potential of combined heat and power (CHP), waste heat from industries and waste incineration. In the absence of available process heat, geothermal and solar thermal sources such as bore fields and solar thermal collectors, emerge as alternatives. A.M. Jodeiri et al. [36] study the technological and non-technological challenges for solar thermal, geothermal, residual heat and biomass energy sources for district heating networks. Eventually, the selected heat source depends on the availability near the demand center and the size of the demand. Heat sources can either be concentrated in one location or dispersed through the network. For this study, two types of heat sources are relevant: geothermal heat sources and solar thermal heat sources. For completeness and future relevance, industrial heat sources will also be addressed.

Geothermal Heat Sources

A common way to harness geothermal heat is through bore fields. A bore field can be modeled as a big ground source heat pump, extracting heat from the ground. Two main types of bore fields can be distinguished: horizontal and vertical bore fields. In a horizontal bore field, the pipes are placed less than twenty meters underground, where the ground temperature is affected by the ambient temperatures. A horizontal bore field requires more land space than a vertical bore field, to ensure a correct spacing of the trenches, maximizing the efficiency. Linwei H. et al. [37], have investigated the performance of three types of horizontal bore fields: linear-loop, spiral-coil and slinky-coil arrangements. For a heating capacity of 5kW, the linear-loop arrangement only needed a length of 66.7m, whereas the other arrangements needed a length of 213m and 239m respectively. The size of the bore fields was kept the same in all three arrangements, covering an area of 73.5m^2 (10.5m x 7m). The average COP of the spiral-coil arrangement was slightly higher than the slinky-coil arrangements, which in turn was slightly higher than the linear-loop arrangement. In reality, the spiral-coil arrangement is used most often. Thermal Earth [38], claims that the area covered by the bore field can be estimated to be 2.5 times the surface of the building. According to Gaoyang H. et al. [39], the power output of a horizontal bore field lies between 40W and 140W per meter trench, depending on the ground temperature.

A vertical bore field extracts the geothermal heat from deep under the ground, with temperature increasing for lower depths, independent of the surface temperature. A vertical bore field consists of one or more boreholes, usually spaced 6m apart, with widths ranging from 15 to 25cm and depths ranging to several hundreds of meters, depending on the location and regulations, requiring less land space to extract a similar amount of heat.

However, The drilling process for the boreholes is much more intensive than the excavation process of the trenches, resulting in a higher environmental and financial cost. In DHNs is usually opted for vertical bore fields, because of lower land use and higher and more stable temperatures, leading to a higher COP. Some important characteristics of a bore field include the number and the spacing of boreholes, the depth, the heat transfer fluid (HTF), the grouting material and the piping type and material. The heat is extracted via single or double U-tubes and transported with an HTF. Apart from the bore field itself, a circulation pump, valves, an expansion vessel and temperature and pressure sensors are required to ensure a smooth and safe operation [40]. According to Thermal Earth [38], one borehole with a width of 20cm and depth of 100m could supply a heating power of around 6kW.

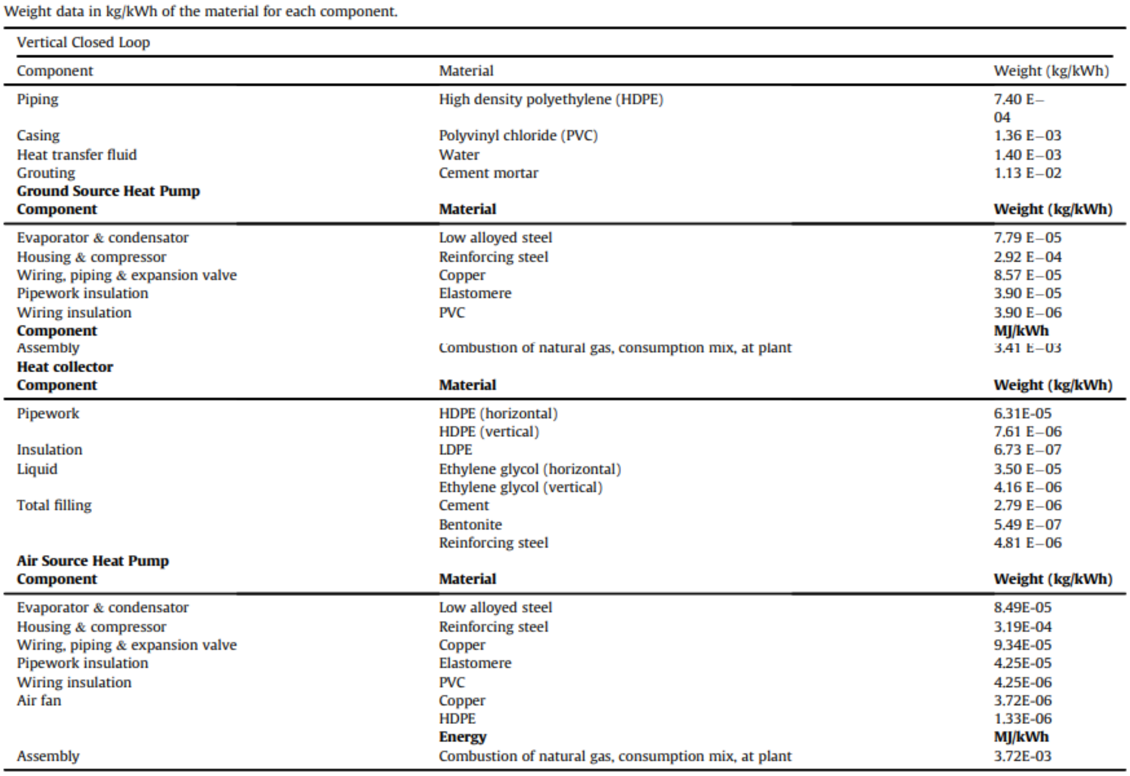
For the casing of the pipes, corrosion-sensitive materials should be avoided. Kaya T. et al. [41], have analyzed the performance of multiple materials for different types of corrosion. The selected alloy or plastic depends on the situation. The use of pipes with a steel casing and plastic inner lining, such as high-density polyethylene (HDPE) or polypropylene (PP) has increased. Lately, fiberglass-reinforced plastics (FRP) have been selected more and more due to their high corrosion resistance, long lifetime, easy installment and low operational cost. After placing the U-tubes, the boreholes are filled with grouting material, also referred to as cement slurries. Boreholes are cemented, to improve contact of the heat-exchanging surface, protect the steel casings from corrosion and increase the thermal conductivity. The steel casing and cement slurries are subjected to harsh conditions, such as high temperatures, different kinds of corrosion and high pressures. Sophia L. et al. [42], give a review of different grouting materials from the 1950s up to 2021. Bett E. et al. [43], describe all kinds of placement techniques and materials for well cementing. The common cement slurries consist of cement, mixed with certain percentages of silica, lignin-sugar bentonite, lime, etc.

After extracting heat from the ground, it is transferred to the heat pump by a heat transfer fluid (HTF) through a network of pipes. In closed-loop systems, this fluid can either be water or an antifreeze solution. Important characteristics of an effective HTF include:

- High **thermal stability** for longer service lifetimes and less maintenance
- Low **viscosity** to minimize the pumping power
- High **Thermal capacity** for more energy storage per kg of the HTF
- Good **Thermal conductivity** for faster heat transfer
- Low **corrosivity** for longer service lifetime and lower cost of the equipment
- **Boiling and freezing points** for a wider temperature range

With its high thermal capacity and low viscosity, water is often utilized. However, in colder climates, anti-freeze solutions, such as propylene glycol and ethylene glycol are more popular. Ethylene is toxic and can cause health issues should it dissolve in groundwater. It is also corrosive, requiring that the system is equipped with corrosive-resistant material, which increases the investment cost. On the contrary, polypropylene is more expensive, creating a trade-off that needs to be considered and is situation-dependent. Similarly, in the case of open-loop systems, additional precautions must be taken for the installation, due to the corrosive nature of the HTF, typically a brine [44].

The heat pump is responsible for elevating the temperature of the extracted heat to the desired level for the network. The main components of a heat pump include the HTF, the compressor, the evaporator, the condenser, the expansion valve and the tubes connecting the different parts, all encapsulated by a housing. While water can serve as HTF, refrigerants are often preferred in colder climates. Until the 1990s, chlorofluorocarbons (CFCs) were used a lot in refrigerators and heat pumps, causing major damage to the ozone layer. Later, these were replaced by hydrofluorocarbons (HFCs), such as R410a and R134a, because of their lower ozone depletion potential (ODP). However, their contribution to climate change is still substantial. Nowadays, a lot of research goes into minimizing the environmental impact of these refrigerants. Natural Heat transfer fluids such as CO_2, propane, and butane exhibit much lower global warming potential (GWP), but are either highly flammable or are limited by their temperature range or have inferior heat transfer qualities. Beyond concerns about global warming and ozone layer depletion, environmental impacts also consider toxicity and groundwater pollution in case of leakage [45]. The material decomposition of a GSHP and ASHP, determined by Violante A. C. et al. [1], in kg per kWh, are presented in table 2.1.



Weight data in kg/kWh of the material for each component.

Vertical Closed Loop

Component	Material	Weight (kg/kWh)
Piping	High density polyethylene (HDPE)	7.40 E− 04
Casing	Polyvinyl chloride (PVC)	1.36 E−03
Heat transfer fluid	Water	1.40 E−03
Grouting	Cement mortar	1.13 E−02
Ground Source Heat Pump		
Component	**Material**	**Weight (kg/kWh)**
Evaporator & condensator	Low alloyed steel	7.79 E−05
Housing & compressor	Reinforcing steel	2.92 E−04
Wiring, piping & expansion valve	Copper	8.57 E−05
Pipework insulation	Elastomere	3.90 E−05
Wiring insulation	PVC	3.90 E−06
Component		**MJ/kWh**
Assembly	Combustion of natural gas, consumption mix, at plant	3.41 E−03
Heat collector		
Component	**Material**	**Weight (kg/kWh)**
Pipework	HDPE (horizontal)	6.31E-05
	HDPE (vertical)	7.61 E−06
Insulation	LDPE	6.73 E−07
Liquid	Ethylene glycol (horizontal)	3.50 E−05
	Ethylene glycol (vertical)	4.16 E−06
Total filling	Cement	2.79 E−06
	Bentonite	5.49 E−07
	Reinforcing steel	4.81 E−06
Air Source Heat Pump		
Component	**Material**	**Weight (kg/kWh)**
Evaporator & condensator	Low alloyed steel	8.49E-05
Housing & compressor	Reinforcing steel	3.19E-04
Wiring, piping & expansion valve	Copper	9.34E-05
Pipework insulation	Elastomere	4.25E-05
Wiring insulation	PVC	4.25E-06
Air fan	Copper	3.72E-06
	HDPE	1.33E-06
	Energy	**MJ/kWh**
Assembly	Combustion of natural gas, consumption mix, at plant	3.72E-03

Figure 2.1: Material decomposition of a GSHP (copied from [1])

Solar Thermal Heat Sources

Besides geothermal, also solar thermal heat can be harnessed. Solar thermal power plants can do this on a larger scale, at higher efficiencies, but this study focuses on the smaller scale collectors. Three major collector types can be distinguished: flat plate, evacuated tube and concentrated collectors. The flat plate collector is based on heat absorption. The solar radiation is captured on a surface, heating the plate, after which the heat is transferred to the HTF. The flat plate collector is generally made of a series of vertically oriented metal tubes. The tubes are connected at the bottom and the top by a horizontal pipe, supplying and extracting cold and hot water respectively. At the cover, a trade-off has to be made between lower reflection losses with a higher cost or lower heat losses with a higher cost. At lower temperatures, no cover is placed, minimizing the reflection losses and system cost. At higher operating temperatures, usually a glass or plastic cover is used, to minimize heat losses. The design and operation of evacuated tube collectors is similar to flat plate solar collectors. However, the metal tubes are replaced by double glass tubes, relying on radiation to extract heat. The vacuum between the two glass layers serves as insulation, effectively minimizing heat loss. This collector type has superior performance, certainly at higher temperatures, but comes at a higher cost. If higher fluid temperatures are desired, concentrating collectors are implemented. Flat mirrors or Parabolic troughs are used to concentrate the radiation onto the tubes. By focusing the solar radiation onto a line or point, much higher temperatures can be reached. This type of collector is usually installed in solar thermal power plants [46].

Generally, in residential settings, the cheaper, flat plate collector is installed. They typically consist of a glass or plastic cover, an air channel, an absorbent plate, tubes or ducts, an insulating layer and an accumulator. The purpose of the cover is to limit heat loss due to radiation and convection. The air channel separates the cover from the absorbent plate. The absorbent plate is designed to maximize the absorption of solar radiation, convert it into heat, and facilitate the transfer of this heat to the circulating fluid. The absorber plate is made of copper or aluminum, facilitating good absorption and thermal conduction. The tubes or ducts, placed in contact with the absorber, also made from copper, enable the fluid to extract the heat from the plate and transport it to a network or to an accumulation tank for storage. The storage or accumulation tank is made of stainless steel, surrounded by a layer of polyurethane (PUR) or rock wool as insulation. Finally, an insulation layer, also PUR or rock wool surrounds the collector except from the cover, again minimizing the overall heat loss of the system. The casing and support are made from stainless steel or aluminum, depending on the durability requirements. For residential purposes, water can be employed as a heat transfer fluid; however, in colder climates such as Belgium, a glycol mixture is typically preferred [47].

Industrial Heat Sources

The possibility of harnessing industrial heat is only briefly touched upon, as the focus of this study mainly lies on the geothermal and solar thermal heat sources. In regions with available process heat from industries, waste incineration, or combined heat and power, this heat can also be used for space heating. Often complex configurations with heat exchangers (HE) are designed, based on pinch technology to optimize heat extraction. Several HE types can be considered based on factors such as the required temperature range, power, efficiency, cost, etc. The most prevalent types include double pipe heat exchanger (DPHE), shell and tube heat exchanger (STHE), coiled tube heat exchanger (CTHE), enhanced tube heat exchanger (ETHE), and plate heat exchanger (PHE). Among these, the STHE is the primary choice for many applications, as it provides a good trade-off between heat transfer at a high efficiency and power at a reasonable cost. The primary components of an STHE include the shell, tube bundle, front head, rear head, and nozzles. Usually, baffles are placed to enhance mixing, by frequently turning the flow [48].

Distribution Network

In the bore field, U-tubes are responsible for the extraction of geothermal heat, requiring good thermal conductivity. In the distribution network, a different HTF might be employed, featuring different characteristics. The selection of the fluid is based on minimizing the pressure drops and heat losses. Between the bore field and the heating network, either a heat pump or heat exchanger is placed, to upgrade or transfer the thermal energy between the two circuits. Various types of heat exchangers are available, but due to the lower temperature of the DHNs, a counter-flow shell-and-tube heat exchanger is considered. Several parameters have to be optimized. To enhance the heat transfer, A high thermal conductivity is required. Further, temperature resistance, corrosion resistance and strength are necessary for a long lifespan. Finally, cost and availability should be accounted for as well. Several materials are used such as stainless steel, copper, aluminum and titanium. The material selection eventually depends on the requirements of the system. In underground applications, strength and low weight are not that important. Therefore, copper is often opted for because of its high thermal conductivity and low cost [49]. Around the shell of the heat exchanger, a jacket of insulating material is placed. Common insulation materials such as polyurethane or mineral wool. Other, more advanced insulation materials such as glass fiber, ceramic fiber or aerogel are available as well [50] [51].

The pipes in the heating network, responsible for the transportation of the heat, require a high thermal resistance to minimize heat losses. Pipelines are usually multilayered, consisting of steel for strength and plastics for insulation. The British Plastic Federation [52] and Mibec Limited [53], describe the advantages of plastic pipelines over steel pipelines. Plastic pipelines are lightweight and are transported on longer sections, allowing for easy installment. They are more flexible, more corrosion-resistant and cost-effective. Steel pipelines on the other hand ensure a longer lifetime under higher operating temperatures and pressures. Because the temperature in heating networks is decreasing, to reduce their losses and increase their efficiency, the installation of plastic pipelines such as polyethylene is growing. To minimize the heat losses, a layer of insulation material is required. Muhammet K [54], compares different kinds of insulation materials and insulation thicknesses for steel pipelines to minimize energy losses. EPS ended up being the insulation material with the smallest payback time. Lately, the use of Fiberglass has been increasing a lot. It has the highest payback time but is a better choice in case a small thickness is required. Other insulation materials that were examined are rock wool, XPS and foam board.

To transport the heat from the source to the consumer, a heat carrier fluid (HCF) is pumped through this heating network. To prevent damage caused by freezing, anti-freeze solutions are often required as HCFs. Giuseppe E. et al. [44], Braven D. et al. [55] and Heinonen et al. [56], discuss the performance of different fluids for ground source heat pumps. Several anti-freeze fluids are discussed: ethylene glycol, propylene glycol, methanol, ethanol, sodium chloride, calcium chloride and potassium acetate. Ethylene glycol is a common antifreeze, but because of its high toxicity, it is not frequently used in ground source heat pumps. If any leakage of the fluid occurs, it might lead to pollution and health problems. Propylene glycol is non-toxic but has a higher viscosity and might cause circulation difficulties at lower temperatures. The salt solutions such as sodium chloride, calcium chloride and potassium acetate, are also non-toxic and non-flammable but might lead to corrosion problems. Methanol and ethanol are common, but flammable and toxic in higher concentrations (ethanol to a lesser extent than methanol) and should be used with care.

To improve the flexibility of heating systems and increase the lifetime of heat pumps, storage tanks are employed, to minimize short cycling of the HPs. These storage tanks are filled with a fluid, storing the thermal energy. Further, they are equipped with a HE to extract the thermal energy from the primary cycle and a mantel serving as a protection and insulation layer. Abhay D. et al. [57], discuss various types of storage tanks with different kinds of heat storage materials such as water, salts, phase-changing materials(PCM), etc. The selected tank depends on the storage temperature, the storage time, the budget and the scale of the application. In this study, low-temperature and short-term storage is considered on a district-scale level. Long-term heat storage such as seasonal heat storage can be applied as well in district heating networks but is not treated in this study. Applications of high-temperature storage can be found in e.g., (solar) thermal power plants. The storage tanks are usually made out of steel or concrete with a layer of insulation, to minimize heat losses. In DHNs, usually, stratified storage tanks are used. The level of stratification is determined by the thickness of the thermocline, which is the region with a certain vertical temperature gradient. Willy V. et al. [58], analyze the characteristics of different insulation materials. The most frequently used insulation materials are organic foams such as PUR, XPS and EPS and inorganic foams such as glass wool and rock wool. The organic foamy materials have a lower conductivity but are more costly. apart from these conventional materials, super-insulation materials including aerogels and vacuum integrate panels (VIP) are sometimes applied. Their cost price however is significantly higher. Apart from the materials, the positioning of the storage tank is sometimes be considered as well. Sanjuan-Delmas D. et al. [59], compare the performance of steel and concrete storage tanks for buried, partially buried and non-buried scenarios.

Internal Heating System

The heat exchanger serves as the boundary between the collective and individual heating systems. The thermal energy extracted from the collective heating system can be utilized for both central heating and domestic hot water (DHW). Typically, the temperature is sufficiently high for central heating, allowing the heat to be directly conveyed to the emission units. In contrast, for DHW, a booster heat pump (BHP) is generally employed to elevate the temperature of the heat from the network to higher, more suitable levels. These BHPs are typically water-water heat pumps, as the fluid used in the individual network is usually water due to its cost-effectiveness, non-toxic and non-flammable nature, and low viscosity. However, a notable disadvantage of using water is the potential for pipe damage due to freezing.

The material of the distribution pipes in the central heating system depends on the time of construction. Before the 1960s, galvanized steel and iron dominated the market. Later, copper gained prominence a as piping material due to its extended lifespan. However, the high cost and labor-intensive installation of copper led to its gradual replacement by plastics such as cross-linked polyethylene (PEX) and chlorinated polyvinyl chloride (CPVC). Currently, PEX has largely supplanted both copper and other plastics, owing to its long life and affordability. An additional advantage of plastics is their flexibility, which facilitates easier transportation and installation. The circulation pumps used in the central heating system are similar to those from the central heating network, only with a lower nominal power.

Rooms are typically warmed using floor heating and radiators. Other heating systems such as convectors or complex HVAC systems exist as well, but are not treated in this study. Radiators are commonly made of cast iron, mild steel, stainless steel or aluminum. The conductivity and price of the materials follow the same order [60]. Floor heating systems typically comprise several layers to ensure efficient heat distribution and structural integrity. The basic structure includes:

- **Insulation layer:** This layer is placed on top of the base concrete layer, minimizing heat loss to the ground and directing heat upwards into the living space.
- **Reflective foil:** Sometimes positioned above the insulation, this layer reflects heat upwards, further enhancing the efficiency of the heating system.
- **Heating pipes:** These pipes, carrying the hot water, are laid out in a specific pattern to ensure even heat distribution across the floor surface.
- **Structural material:** To increase the thermal capacity and ensure a stable structure, a layer of cement screed is typically applied over the heating pipes.

Guobing Z. et al. [61], investigate the performance of different heat-storing materials and pipes. As heat-storing material, sand and different types of phase-changing materials (PCM), are compared. Fewer temperature variations are observed when PCMs are used compared to sands, because the heat is stored as latent heat instead of sensible heat. The discharge time is also much higher for PCMs. For heating pipes, the study compares polyethylene coils and capillary mats. These capillary mats consist of small plastic tubes densely packed, allowing for a uniform surface temperature distribution. Other piping materials are polybutylene (PB) and polyethylene (PE) multi-layers [62]. In practice, the pipes are spaced 10, 15 or 20cm form one another, amounting up to 10, 7 and 5meters of piping per square meter [63]. Spacing pipes more than 20cm apart may result in the formation of alternating hot and cold sections on the floor, commonly referred to as zebra patterns. Reducing the spacing between pipes enhances thermal power output despite increased costs, enabling the utilization of lower water temperatures.

The insulation layer is usually made of polystyrene (PS), fiberglass, polyester or polyurethane (PUR) [64]. Jian L. et al. [65], compare the performance of floor, ceiling, wall radiator and stratum ventilation heating systems for residential buildings based on an occupied zone predictive mean vote (OPMV), energy use and exergy use. Calin S. et al. [66], assess the performance of a GSHP and compare the use of radiators and floor heating. The employment of floor heating leads to a slightly higher (4.5%) COP of the heat pump, compared to the radiators, because of lower operating temperatures. Also, the on/off cycling in the case of radiators is three times higher than with floor heating, decreasing the lifespan of the heat pump. Additionally, floor heating facilitates a more uniform temperature distribution within the room, thereby enhancing thermal comfort. Conversely, its higher thermal inertia and lower heating power present challenges for control, occasionally resulting in difficulty achieving the desired temperature and subsequent lower thermal comfort. To address this issue, floor heating is often complemented with radiators and possibly an electric booster unit, offering more responsive temperature regulation and improving overall thermal comfort.

2.3 Conclusion

This literature review first compared two types of environmental impact assessment methods: the LCA method and the scoring method. The LCA method was found to be the most suited for this study, as its focus lies on the estimation of the environmental impact. Scoring tools are less accurate, including also economic and social impacts. To this end, the existing MMG KU Leuven method will be used, enabling the analysis of the environmental impact of neighborhoods. Subsequently, a detailed decomposition of individual and collective heating systems was carried out, by first dividing the different systems into a heat generation, heat distribution and heat emission system. This was followed by a further deconstruction of these parts into their components. For each component, different material decompositions were analyzed.

Chapter 3

Methodology

In this study, the environmental impact of collective heating systems will be analyzed. To this end, the assessment method will be applied to a case study, i.e. the social housing district *De Schipjes* in Bruges, from which the heating system has recently changed to a collective heating system. The chapter commences with a description of the use case, followed by a discussion of the procedures and working principles of the applied MMG method. Following this, the different elements will be modelled in the MMG Excel tool, starting with the building elements. Subsequently, a breakdown of all the scenarios and their heating systems is provided. After defining all the scenarios, the modeling of these systems in the MMG Excel tool will be elucidated.

3.1 Use Case Description

De Schipjes is a Belgian social housing neighborhood in Bruges, consisting of twelve buildings, and was extensively renovated in 2014. Since it was classified as heritage in 2009, some restrictions were imposed on this renovation. As part of this renovation, a fully renewable-based heating network was constructed, providing heat for the twelve buildings. Figure 3.2, gives a representation of all the components in the network.

Jansen J. et al [4] describe the decomposition of the collective heating network, which is also depicted in figure 3.2. The main heat source is a 42kW ground source heat pump (GSHP). This heat pump upgrades the heat extracted from a vertical bore field, consisting of 8 holes with each a depth of 125 meters. As an additional heat source, solar thermal collectors (STCs) were installed, covering a total area of $14m^2$. The STCs boost the heat output of the collective system on sunny days. Both the GSHP and the STCs are connected to separate 950-liter storage tanks (WT1 and WT2 respectively), placed in series. The purpose of the storage tanks, is to store the generated heat and separate the distribution network from the heat generation units. This allows for more flexibility and optimal control, ensuring a longer lifetime and better performance of the GSHP and circulation pumps, at the expense of a small heat loss. In the distribution network, the heat is extracted from the water tanks and conveyed through a piping network (with a length of 177m), to substations located at each building. At these substations, the heat is transferred from the distribution network to the individual networks of the buildings through a heat exchanger. The heat transfer is controlled via a control valve (V2). A bypass valve (V1) ensures a minimal mass flow rate through the circulation pump (P4), in case a low heat demand is required in the buildings. Inside the buildings, the heat is distributed with a combination of radiators in each room and floor heating at ground level, regulated by more control valves (V3 and V4). Given the relatively low temperature of the heat from the district heating network, each building is equipped with a booster heat pump to upgrade the low-temperature heat for domestic hot water, stored in a 90L storage tank (WT3). Several circulation pumps provide circulation of the fluids (P1...P6).

The temperature of the supply and return line at the secondary side of the GSHP are set to 50°C and 40°C respectively. This is similar for the supply and return line of the distribution network after WT2 and for the central heating in the building. The maximum temperature of the preheating tank (WT1) is 60°C. The temperature set point for DHW at the secondary side of the BHP is also 60°C.

FIGURE 3.1: *De Schipjes* (copied from [2] and [3])

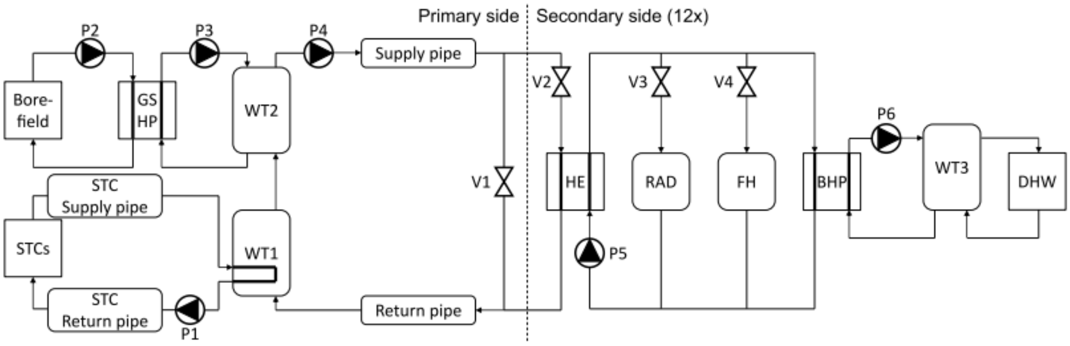


FIGURE 3.2: Collective heating system of *De Schipjes* (copied from [4])

3.2 Working Principle of the Selected LCA Methodology

In this section, the procedure and operational principle of the selected LCA methodology are enlightened. This is followed by a discussion of its subdivision into different life cycle phases, the choice of the impact indicators, the hierarchical structure, and the functional units.

3.2.1 MMG KU Leuven Tool

In this master thesis, the MMG KU Leuven tool is used, which is an expert tool based on the MMG LCA method and developed by the division Architectural Engineering from the KU Leuven. However, the applied LCA methodology follows the implementation of the MMG LCA method in the TOTEM tool. An extensive breakdown of the working principle of the MMG KU Leuven tool and TOTEM tool is given in the PhD from Trigaux D. [15] and a report from TOTEM [5]. This is narrowed down to a summary of the most important aspects needed for this study. The MMG KU Leuven tool is implemented in a number of Excel Spreadsheets. As previously mentioned, this tool assesses both environmental impact and financial costs through a life cycle methodology. The financial cost is calculated using life cycle costing (LCC), while the environmental impact is evaluated via an environmental life cycle assessment (E-LCA). To determine the total environmental impact of a system, various approaches are used, in LCA tools, to aggregate environmental indicators to a single score. Some examples are environmental cost methods, distance to target, panel weighting, etc. In the MMG KU Leuven and TOTEM tool, these are integrated via a weighting approach, developed in the context of the European Product Environmental Profile (PEF) points. Apart from environmental and financial factors, also the building qualities can be evaluated, based on a multi-criteria assessment (MCA). This assessment ensures that the reduction in environmental and financial impact does not come to the detriment of provided building qualities such as comfort. Because in this study, the focus lies on the total environmental impact of an energy system, only the environmental impact indicators are considered. LCA methodologies are often database-driven, as they require extensive data on building materials and components. The LCA data used in both the TOTEM web tool and the MMG KU Leuven tool are mainly retrieved from the Swiss database Ecoinvent (version 3.6) or Belgian Environmental Product Declarations (B-EPD).

As previously stated, the environmental impact is assessed using multiple indicators, which will be discussed in more detail. Each indicator has its own unit. To compare the different indicators or aggregate them to a single score, they should be expressed in the same unit. Previously, this was achieved via a monetization approach, quantifying the costs required to prevent or mitigate the damage caused by environmental impacts to a predefined level of sustainability. Following the revision of the European standard EN 15804+A2 in July 2021, a decision was made to transition to the PEF weighting approach, developed by the European Commission, to align the MMG approach more closely with European advancements on LCA. Under the PEF methodology, the environmental impact of each indicator is multiplied with a certain normalization and weighting factor, hereafter expressed in milli-points (mPt). This enables the comparison of environmental impact between the different indicators. Additionally, it facilitates the determination of the total environmental impact of a system by aggregating over all indicators. This approach allows for the comparison of different heating systems, both based on individual indicators and on an aggregated score. An overview of all the indicators, their functional units and the PEF-aggregation factors is given in section 3.2.3.

Most of the LCA data is exported from Simapro. The modeling of the components themselves is done in the tool. Simapro is an LCA software, in which LCA data of materials, energy, transportation and end-of-life processes is gathered. Simapro, in turn, retrieves this data from several databases, from which the Swiss database Ecoinvent is the most important for LCA practitioners. Ecoinvent database has several versions, due to updates over the years. In this study, version 3.6 is consulted, as this is the version used in TOTEM and the MMG KU Leuven tool. Most of the components used in this study are from Simapro and thus the Ecoinvent database. If an element is not present in either of the databases, other sources were consulted. In this case, components and materials were built up based on information from other academic studies or based on datasheets from private companies.

3.2.2 Life Cycle Stages

According to the life cycle approach applied, the lifetime of each component is subdivided into multiple life cycle stages: product stage, construction process stage, use stage and end-of-life stage. These stages are further split into modules such that they are in line with European standards (CEN 2010, CEN 2011 and CEN 2015). A clear representation of the different stages and modules is depicted in figure 3.3. Following TOTEM, the environmental impact of the building is determined for each stage, over a life span of 60 years.

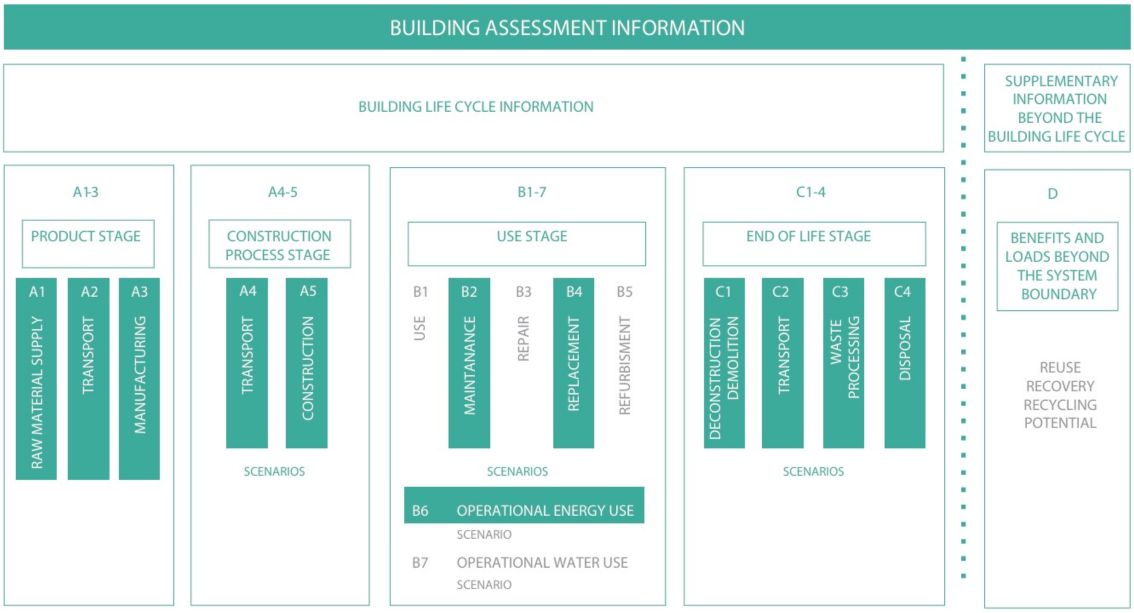


Figure 3.3: Life cycle stages according to the EN A15805+A2 standard (copied from [5]), the modules in green are included in the assessment

The product stage includes three modules: The extraction of raw materials (A1), transportation of the extracted materials (A2) and the manufacturing of the products (A3). The transportation (A4) and construction of the products (A5), are part of the construction process stage. The use stage considers all the processes during the operation of the system, between the end of construction and the demolition. Not only the operational energy use (B6) but also water use (B7), maintenance (B2), repair (B3), refurbishments (B5) and replacements (B4) are included. The energy use is either electricity, gas or other fuels, used for space heating, domestic hot water production and ventilation. Apart form the building elements, maintenance and replacements of components from the heating system during the lifetime of the building are considered.

The end-of-life stage covers the impact of the deconstruction and demolition (C1) of the system, as well as the waste transport (C2), processing (C3) and disposal (C4). The system is assumed to be completely demolished, without considering the residual value of components that have not reached the end of their service life. The benefits from recycling, reuse, or energy recovery of specific materials is addressed by the waste processing module, but is not included in TOTEM. The waste disposal module incorporates the impact of all sorting, incineration and landfill processes. In this master thesis, and in line with the TOTEM tool, not all modules are included. Only the impact of the modules, indicated with a green box, are considered in this study.

3.2.3 Environmental Impact Indicators

The objective is to assess the total environmental impact, which is not determined by climate change only. Other environmental indicators should be included as well. A list of all the indicators proposed by the EN 15804+A2 standard as well as their units and PEF-aggregation factors are shown in table 3.1. As mentioned before, the representation in units as well as in mPt, allows the comparison of the impact based on the individual indicators as well as a single score.

Environmental impact indicators	**Unit**	**PEF-factor [mPt/unit]**
Climate change - fossil	kg CO_2 eq.	0.026009
Climate change - biogenic	kg CO_2 eq.	0.026009
Climate change - LULUC	kg CO_2 eq.	0.026009
Ozone depletion	kg CFC 11 eq.	1176.1840
Acidification of soil and water	mol H^+ eq.	1.1160
Eutrophication aquatic fresh water	kg P eq.	17.42440
Eutrophication aquatic marine	kg N eq.	1.514344
Eutrophication terrestrial	mol N eq.	0.209912
Photochemical ozone creation	kg NMVOC eq.	1.177314
Depletion of abiotic resources - minerals and metals	kg Sb eq.	1186.1050
Depletion of abiotic resources - fossil fuels	MJ, NCV	0.001280
Water use	m^3 world eq. deprived	0.007420
Particulate matter emissions	Disease incidence	150528.0
Ionizing radiation - human health	kBq U235 eq.	0.011874
Ecotoxicity - freshwater	CTUe	0.000450
Human toxicity - cancer effect	CTUh	12660384.90
Human toxicity - non-cancer effects	CTUh	80113.60
Land use related impacts/ Soil quality	-	0.000097

Table 3.1: Environmental impact indicators [15]

3.2.4 Hierarchical Structure

In the LCA methodology used in the TOTEM tool, a bottom-up approach is used, distinguishing four levels: materials (e.g. PUR, brick, copper), components (e.g. tubes, brickwork, heat pump), elements (e.g. wall, roof, heating system) and building. In the PhD from Trigaux D. a neighborhood is defined as a combination of buildings, networks (e.g. roads, utilities and district heating) and open spaces (parks, squares, etc.). This addition of district heating is useful for this study. This master thesis follows this division, but only considers buildings and district heating. Other networks and open spaces are excluded. This is because the assessment of heating networks only requires the modeling of buildings and district heating. The integration of other neighborhood elements e.g. the streets, open spaces and gardens, does not contribute to the analysis of the environmental impact of the heating networks. The four levels used in the TOTEM tool, apply to both the buildings and to district heating.

3.2.5 Functional Unit

Depending on the scale and type of the element, different functional units are used. The elements are divided into four different groups: scalar elements, linear elements, planar elements and volumetric elements. Scalar elements, such as a technical installation, window door, etc., are quantified by the number of occurrences in the building. Linear elements such as beams and columns, are characterized by their length, defined in meters. Planar elements, like walls and floors, are expressed in square meters. Finally, volumetric elements, such as heated volume are expressed in cubic meter. The components from the different elements can be subdivided in similar groups. Materials can be quantified in kilograms or cubic meters.

3.3 Building Decomposition

To enable the assessment of individual and collective heating systems, first the lay out of the buildings in the district has to be identified. In the case of *De shipjes*, all buildings show similar lay outs, facilitating a simplified approach. This permits the modeling of the entire neighborhood by simulating a single version shared across all twelve buildings. This single version was developed by consulting several sources, such as the paper from Jelger Janssen [4], a paper from Van De Velde S. et al. [67] and Van Kenhove E. et al. [68]. Due to differing objectives in these papers, certain necessary information regarding building elements was absent. To address these information gaps, a reference model from TOTEM was consulted. For Materials, such as aerogel or VIP panels, that are not yet available in the MMG tool, suitable alternatives were selected. As mentioned before, the buildings were recently renovated. But in this analysis, they will be modelled as newly-build, to get a better representation of the total building impact. All the building elements are considered to have a lifetime of 60 years.

The buildings comprise two stories: a ground floor covering an area of $30.7m^2$ and a first floor spanning $17.7m^2$. Both floors are constructed with reinforced concrete and cement screed, and are finished with either ceramic or linoleum tiles. Waterproofing is ensured by a PE or PP proofing sheet. Additionally, the ground floor is insulated with a layer of PUR to reduce ground-coupled heat losses. The building is topped with a pitched roof, comprising a rafter as the primary structural element, stone wool for insulation, and a Gypsum plasterboard for internal finishing. As an exterior finish, the roof is adorned with ceramic tiles. In the scenario with a heat pump, floor heating is embedded in the ground floor; however, this is modelled in the heating system rather than the building elements.

The windows and doors utilized in the model are based on reference models from TOTEM and are commonly found in Belgian households. The windows are constructed with a hardwood profile and double glazing filled with argon, providing excellent insulation properties. The entrance door (door 1) is crafted from a hardwood profile and features a panel made from steel, wood, and aluminum, while the internal doors (door 2) are composed of MDF. An overview is provided in table 3.2.

Element	Materials
Ground floor	
	Excavation process
	Loose filling (300 mm)
	Reinforced concrete (150 mm)
	Proofing sheet - PE (0.2 mm)
	PUR board (100 mm)
	Screed - Cement (50 mm)
	Rigid tiles - Glazed ceramic (300x300x10 mm)
First floor	
	Film coating - Acrylic paint
	Gypsum plasterboard (12.5 mm)
	Proofing sheet - PP (0.22 mm)
	Reinforced concrete (200 mm)
	Screed - Cement (50 mm)
	Soft tiles - Linoleum (2.5 mm)
Pitched roof	
	Film coating - Acrylic paint
	Gypsum plasterboard (12.5 mm)
	Stone wool blanket (175 mm)
	Rafter - Treated softwood (63x175 mm - ctc 500 mm)
	Vapour barrier - PP (0.22 mm)
	Counter battens - Treated softwood (30x20 mm)
	Rigid tiles - Glazed ceramic (246x195 mm)
Window	
	PVC profile
	Double glazing - Argon filling (24 mm)
Door 1	
	Profile - Hardwood (70 mm)
	Panel - Steel/wood/Aluminum (900x2050 mm, t= 70 mm)
Door 2	
	Profile - MDF (for 160 mm)
	Panel - MDF (900x2050 mm - t=40 mm)

Table 3.2: Building elements - Floor/Roof/Window/Door

To get a better overview of the wall placements, the top view of the building envelope is presented in figure 3.4. The composition of the various walls is outlined in table 3.4. With the exception of the walls separating the toilet and the yard and the kitchen and the yard, all the external walls adhere to the composition described in the table as ’External wall 1’. The main supporting structure is a double brick layer, enclosing an air cavity with a glass wool blanket as an insulating layer. All walls in the building are internally finished with gypsum plaster and acrylic paint. The wall between the toilet and the yard also compromises a double brick layer with a similar insulating layer, described as ’External wall 2’. However, The width of the layers slightly differs, resulting in a lower overall thermal resistance of the wall. The wall between the kitchen and the yard, defined as ’External wall 3’, is built up differently. It consists of a wooden supporting structure with a blanket of stone wool as insulation. The exterior is finished with an OSB and a wood fiber board.

The internal walls are configured as outlined in the table under the designation 'Internal wall'. As a high thermal resistance is not required, the walls can be significantly thinner. They only compromise one layer of bricks, enclosed on both sides with gypsum plaster and finished with acrylic paint. The common walls, referred to as 'Common wall', consist of a double layer of bricks, enclosed by a gypsum plaster on both sides and finished with acrylic paint. The dimensions of all building elements are represented in table 3.3

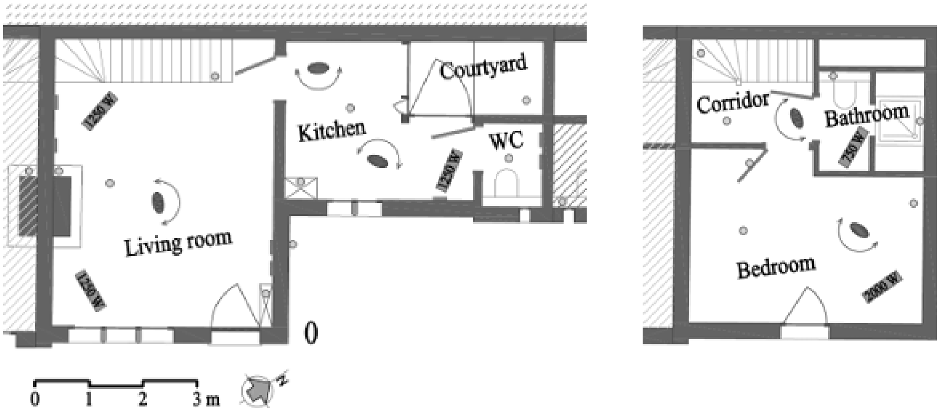


Figure 3.4: Building enveloppe (copied from [4])

Element	Area/pieces	U-value $[W/m^2K]$
Ground floor	30.7 m^2	0.22
with floor heating	29.0 m^2	-
without floor heating	1.7 m^2	-
First floor	17.7 m^2	6.18
Pitched roof	30.7 m^2	0.27
External wall 1	68 m^2	0.23
External wall 2	9 m^2	0.40
External wall 3	3 m^2	0.29
Internal wall	21 m^2	1.38
Common wall	41 m^2	0.9
Window	12.2 m^2	1.55
Door 1	1 piece	1.60
Door 2	4 pieces	0.00

Table 3.3: Building elements - characteristics [4]

Element	Materials
External wall 1	
	Hollow bricks laid in cement mortar - Fired clay (288x188x138 mm)
	Air cavity - Not ventilated (50 mm)
	Cavity ties - Steel (180x3.5 mm)
	Insulation clips - PVC
	Glass wool blanket (130 mm)
	Bricks laid in cement mortar - Fired clay (188x88x48 mm)
	Gypsum plaster (12 mm)
	Film coating - Acrylic paint
External wall 2	
	Hollow bricks laid in cement mortar - Fired clay (288x188x138 mm)
	Air cavity - Not ventilated(60 mm)
	Insulation clips - PVC
	Glass wool blanket (60 mm)
	Bricks laid in cement mortar - Fired clay (188x88x48 mm)
	Gypsum plasterboard - Including joint filler (12.5 mm)
	Film coating - Acrylic paint
External wall 3	
	Bituminised wood fibre - Screwed board (18 mm)
	OSB board (18 mm)
	Stone wool blanket (100 mm)
	Nailed softwood frame - Untreated Belgian mix (100 mm)
	Gypsum plaster (12 mm)
	Film coating - Acrylic paint
Internal wall	
	Film coating - Acrylic paint
	Gypsum plaster (12 mm)
	Hollow bricks laid in cement mortar - Fired clay (288x188x138 mm)
	Gypsum plaster (12 mm)
	Film coating - Acrylic paint
Common wall	
	Film coating - Acrylic paint
	Gypsum plaster (12 mm)
	Hollow bricks laid in cement mortar - Fired clay (288x188x138 mm)
	Hollow bricks laid in cement mortar - Fired clay (288x88x138 mm)
	Gypsum plaster (12 mm)
	Film coating - Acrylic paint

Table 3.4: Building elements - Walls

3.4 Heating Systems

In this section, the different scenarios and their heating systems will be defined. Later, a comparative analysis of several scenarios with individual heating systems and one with a collective heating system will be conducted. The different individual heating systems will be specified first, as these will form the basis for the collective heating system later on. To perform an LCA, all these systems will have to be modelled in the MMG tool. As with the building elements, the material decomposition, lift time, maintenance, etc. will have to be defined for each component. Materials, components or elements that were not available in simapro were built up based on information from other academic studies or datasheets from private companies.

3.4.1 Individual Heating Systems

Most Belgian households are heated separately, each by their own heating system. These individual heating systems consist of a heat generation unit, a heat distribution network and heat emission units.Below, a breakdown of the distinct sections within the heating system is provided.

Heat Generation Unit

First, the generation unit is discussed. The heat generation units are responsible for the heat production or generation. five different individual scenarios will be examined in this study: a gas boiler, electric heating, an air-source heat pump, a GSHP with a horizontal bore field and a GSHP with a vertical bore field. A summery of the different generation types and their components is shown in table 3.5. The components are either based on an existing predefined component from Simapro or self-made, based on a datasheet or information from other sources.

The gas boiler and electric boiler utilize gas and electricity, respectively, as energy source. Compared to a HP, both boilers require only a small amount of raw materials for their production. Further, their heating is much more flexible than a HP, with a lower lead time. Conversely, the efficiency of the heat generation of both boilers is significantly lower, due to the high COP of the HPs. The gas boiler used in this study, is a model, already predefined in Simapro. It has a nominal heating power between 5 and 35 kW and consists of a mixture of metals and plastics. For the scenario with electric heating, both an electric boiler and electric radiators are employed for DHW and central heating respectively. The electric radiators will be treated in the section about emission units. The electric boiler, is based on an auxiliary heating unit of 5kW in combination with a storage vessel of 90 l. Both components are already predefined in the MMG tool. A heating power of 5kW for DHW is way to high for these houses, but the design and mass of these units does not vary to much with their power for these lower ranges. In the MMG method, the mass is generally used to extrapolate LCA data across similar components, making it a viable approximation. The storage vessel of 90 l is again modelled via a mass-based extrapolation of a 600 l water tank with a mass of 283 kg.

Aside from boilers, heat pumps show a lot of potential and are more and more deployed as a heat source in buildings. A heat pump uses electricity to upgrade heat extracted from the environment. Despite the lower flexibility, HPs usually operate at higher efficiencies, depending on their COP, leading to an operational energy use. However, many more materials are required for their production and construction. Three types of HPs are distinguished in this study: an ASHP, a GSHP with horizontal bore field and a GSHP with vertical bore field. All three components are derived from a predefined generic component in Simapro, which is also used in the TOTEM tool. Initially, existing components were modelled, based on PEP datasheets (Product Environmental Profile) from manufacturers, containing LCA information. However, the data deviated to much from the generic data and background information about the product and the implemented LCA method was lacking. These deviations appear to have significant implications for the final results, particularly concerning the substantial environmental impact of the heat pump. Hence, the decision was made to model the base case utilizing the predefined generic component available in Simapro. The results from the PEP datasheets will be analyzed in a separate analysis, which will be conducted in section 5.1.

The component used in this scenario is the same as the one used in the TOTEM tool, modeled through a mass-based extrapolation of a predefined 130.09 kg GSHP from Simapro, based on generic data. The ASHP has a nominal heating power of 9 kW and a mass of 205 kg. The employed heat transfer fluid is 3.09 kg of the refrigerant R134a. In the model, a leakage of 2% per year is considered, verified by the various datasheets form the other heat pumps. Because the refrigerants are expected to have a significant environmental impact, their effect will be examined further in section 5.2. However, the correctness of this mass-based extrapolation is questionable, as an ASHP and GSHP, usually have slightly different designs. The main differences are the size of the evaporator and some supplementary components, such as a ventilator and air shafts, water pipes and circulation pump, on the primary side. To achieve the same heating capacity, a larger evaporator is required for the ASHP, due to the reduced heat exchange resulting from the lower thermal capacity and lower thermal conductivity of the air. Despite these differences, the material fractions in the different heat pumps seem similar, which was verified by the proposed material decompositions by Violante A.C. et al.[1] in figure 2.1. Additionally, this was checked by comparing the different PEP datasheets, which can be found in appendix A.

For the GSHPs, a similar approach was taken. The selected component is again a component used in Totem, with a mass of 129 kg, based on a mass extrapolation from the predefined 130.9 kg GSHP from Simapro. The fluid responsible for the heat transfer in the HP is again 3.09 kg of the refrigerant R134a. The big difference in mass shows again the difference in layout between both HPs. However, the source of information from the heat pumps is unknown. The extra analysis on the impact of different heat pumps in section 5.1, will give some more nuance to the results obtained from the use case.

The major difference between a GSHP and an ASHP is the source from which they extract heat. An ASHP upgrades the heat from the outside or inside air and only needs a ventilator with some air shafts for air circulation. A GSHP extracts heat from the ground through a bore field, using a circulation pump for the heat transfer fluid (HTF). Two types of bore fields are under consideration: horizontal and vertical. The decomposition and required size of the bore fields are discussed in the literature study.

In a horizontal bore field,. the pipes are placed at a depth of 1.6 m, in trenches with a width of 0.8 m. After placing the pipes, the trenches are filled up with the excavated sand. Some types of grouting material can be utilized to enhance heat exchange, although this is typically not done in practice. For the dimensions of the bore field, several sources were consulted. Linwei H. et al. [37] found that a bore field covering an area of 73.5 m^2 would be able to supply 5 kW for heating. Thermal Earth [38] on the other hand, claims that the area covered by the bore field can be estimated to be 2.5 times the surface of the building, amounting to 125 m^2 for the use case. Other studies gave estimations of the trench length. according to Gaoyung H. et al. [39], the pipes run twice through the same trench (back and forth), supplying about 90 Watts per meter. Other research [69], [70] and [71], claimed that a horizontal bore field supplies between 20 W/m and 70 W/m depending on the temperature and structure of the ground and on the placement technique of the loops.

Component	**Material**	**Source**
Gas boiler	Metals and plastics (40 kg)	Simapro
Water tank (90l)	Metals and plastics (26 kg)	Simapro
Gas pipe (OD = 28mm, t= 3mm)	Galvanized steel (1.9 m)	Simapro
Electric boiler (5kW)	Metals and plastics (10kg)	Simapro
Water tank (90 l)	Metals and plastics (26 kg)	Simapro
ASHP (9 kW)	Steel and plastics (202 kg)	Simapro
Refrigerant	R134a (3.09 kg)	
Water tank (90l)	Metals and plastics (26 kg)	Simapro
GSHP (9.7 kW)	Metals and plastics (126 kg)	Simapro
Refrigerant	R134a (3.09 kg)	
Water tank (90 l)	Metals and plastics (26 kg)	Simapro
Bore field - horizontal		
Excavation process	Soil ($1.6 * 0.8 * 125\ m^3$)	Simapro
Expansion vessel (25 l)	Metals and plastics (4.50 kg)	Simapro
Control valves	Metals and plastics (4 pieces)	Simapro
Sensors (P en T)	Metals and plastics (6 pieces)	Simapro
Circulation pump (40-100 W)	Metals and plastics (2.40 kg)	Simapro
Fluid	Glycol-water 25% (260 kg)	Simapro
Pipes (OD = 32 mm, t= 2.3 mm)	PE (2x175 m)	Simapro
Bore field - vertical	one borehole (100 m)	
Drilling process (diameter = 200 mm)	Soil (100 m)	Simapro
Expansion vessel (25 l)	Steel (4.50 kg)	Simapro
Control valves	Metals and plastics (4 pieces)	Simapro
Sensors (P en T)	Metals and plastics (6 pieces)	Simapro
Circulation pump (40 - 100 W)	Metals and plastics (2.40 kg)	Simapro
Fluid	Glycol-water 25% (270 kg)	Simapro
U-tubes (OD = 32 mm, t = 2.3 mm)	PE (4x100 m)	Simapro
Grout (33/33/33 mass%)	Cement/bentonite/silica (2.8 m^3)	*Boringen Verheyden* and [42]
Spacers	PE (40 g/piece, 40 pieces)	Simapro

TABLE 3.5: Individual heating system - Generation part

The horizontal bore field can now be modelled, bringing all these considerations together. For the sizing of the bore field, a required heating power of 5 kW was determined, which will be enlightened further, in section 3.5 about the energy calculations. The requisite trench length was estimated via a weighted average of the heat exchange rate, to be 40W/m. The weighted average was necessary because the heat exchange rate heavily depends on the ground temperature, influenced by the geographical location of the bore field and the time of the year. To reach a heating power of 5 kW, a trench length of 125 meters ($5kW/40W/m$) is required. The total covered area can then be calculated by considering 5 trenches of each 25 m, spaced 3 m apart. This amounts to a coverage of about $300m^2$ ($25m * 3m * 4$), which exceeds the previously stated value.

The vertical bore field is modelled based on the information from Thermal Earth [38], stating that one borehole with a width of 20 cm and a depth of 100 m can provide 6 kW of heating. The vertical bore field consists of one borehole, with a width of 200mm and a double U-tube, reaching a depth of 100 m. The pipes used for both bore fields are made from PE and have an outer diameter of 33 mm and a thickness of 2.3 mm. The information regarding the grouting material, utilized to fill part of the trenches and the borehole, was obtained from *Boringen Verheyden*, and a paper by Sophia L. B. et al. [42]. The selected mixture comprises cement, bentonite, and silica, with mass percentages of 33%, 33%, and 33%, respectively.

Some additional equipment is required for the smooth operation of both bore fields. A circulation pump with a power between 40 W and 100 W ensures the circulation of the fluid. Further, an expansion vessel of 25 l is needed to keep the pressure constant, in case of thermal expansions. Together with the pump, control valves regulate the flow rate through the pipes. To stabilize the vertical bore field infrastructure, spacers are positioned every three meters. Finally, sensors are placed at the entry and exit of the heat pump, to monitor its performance. The heat transfer fluid in the bore field is an antifreeze water-glycol solution (25%). A list of all the components present in the bore fields is given in table 3.5.

Heat Distribution Network

After generating or extracting the heat, it needs to be conveyed to the place of emission. A network of pipes, sensors, valves and a circulation pump fulfill this purpose. Apart from the heating network, also the sewer and ventilation system are modelled in this part. The network for the use case, is based on a default layout from the Totem tool. Various types of multilayer pipes for hot water distribution, as well as sewer pipes and ventilation shafts, constitute the network. However, this model needed resizing, as the predefined model in the Totem tool is based on a dwelling with a useful floor area (UFA) of 150 m^2 and the UFA of the dwellings in the use case is only 50 m^2. Therefore, the model for the heating network and ventilation shafts used in this study was estimated to be 75% of the length of the reference model. The length of the sewer pipes was kept the same, as the distance to the street is nearly independent of the building size. An overview is given in table 3.6. In the scenario with an electric boiler, only the DHW needs to be distributed. The central heating happens on-site and does not require any additional distribution.

Heat Emission Units

The generated heat is directed towards the site of emission. In Belgium, the heat is generally emitted by radiators. However, other technologies, such as floor heating, convectors, climate ceilings, etc. have been implemented as well. This study will focus mainly on radiators and floor heating, as they are prevalent in residential buildings. In buildings equipped with a gas boiler, the emission is usually done by radiators. If the heat is generated by a heat pump, the option for floor heating is often considered as well. Floor heating is a much bigger asset in the case of a heat pump, because the performance improves significantly with lower temperatures. Radiators, in contrast, operate on radiation-based

Component	**Material**	**Source**
Central heating network		
Multilayer pipe (OD = 26 mm, t = 3 mm)	PEX-Al-PEX (9.225 m)	Simapro
Multilayer pipe (OD = 20 mm, t = 2 mm)	PEX-Al-PEX (2.400 m)	Simapro
Multilayer pipe (OD = 18 mm, t = 2 mm)	PEX-Al-PEX (0.600 m)	Simapro
Multilayer pipe (OD = 14 mm, t = 2 mm)	PEX-Al-PEX (1.875 m)	Simapro
Circulation pump (40 - 100 W)	Metals and plastics (2.40 kg)	Simapro
Expansion vessel (25 l)	Steel (4.50 kg)	Simapro
Hydro collector	Brass-inox (19 mm)	Simapro
Sewage disposal		
Pipe (OD = 32 mm, t = 3.3 mm)	HDPE (3.075 m)	Simapro
Pipe (OD = 40 mm, t = 3 mm)	PVC (1.725 m)	Simapro
Pipe (OD = 50 mm, t = 3 mm)	PVC (3.300 m)	Simapro
Pipes (OD = 75 mm, t = 3 mm)	PVC (0.800 m)	Simapro
Pipes (OD = 90 mm, t = 3 mm)	PVC (14.100 m)	Simapro
Ventilation system		
Ventilation unit (150 – 250 m^3/h)	Metals and plastic	Simapro
Round duct (OD = 160 mm)	galvanized steel (14.0 m)	Simapro
Window vent (80 - 94 mm)	Al-PVC (2.7 m)	Simapro
Round grid (OD = 125 mm)	Steel (3 pieces)	Simapro
Roof hood (OD = 160 mm)	Galvanized steel (1 piece)	Simapro
CO_2 sensor	Metals and plastics (2 pieces)	Simapro
RH sensor	Metals and plastics (2 pieces)	Simapro

TABLE 3.6: Individual heating system - Distribution part

heat exchange, necessitating higher temperatures due to the fourth-order relationship with the temperature(T^4) of the radiative heat exchange. For the use case, a heat emission power of 5 to 6 kW was pursued. In the scenario of the electric boiler, electric radiators are employed, generating the heat on site.

The panel radiator used in this study, is an already predefined model. It consists of a mixture of low-alloyed steel and rolled steel, finished with alkyd white paint. The heating output of the radiator is controlled by a thermostatic valve, composed of casted brass and moulded, low-density PE. The model of the electric radiator was based on data from several manufacturers, [72], [73], [74] and [75]. It has a heating power of 2 kW and is made of 40 kg low alloyed steel plates.

The floor heating itself was based on a floor heating component from TOTEM, placed in the layer of cement screed. It is a multi-layer pipe, composed of PEX and ALuminum, with an outer diameter of 40 mm and a thickness of 4 mm. The length and positioning are based on information from *Verwarmingswinkel* [63]. In the use case, the ground floor is heated through floor heating, spacing the pipes 15cm apart for 10 m^2 and 20 cm apart for 20 m^2. The total length of the floor heating pipes was calculated to be 170m. Another option is to place the pipes on positioning mats from polystyrene (PS). Due to the lower therm al conductivity of PS, the mats can also serve as an insulation layer. A summary of all the components present on the emission side is given in table 3.7

Component	Material	Source
Panel radiators	Steel and alkyd paint (20kg)	Simapro
Thermostatic Valve	Metals and plastics (0.5kg)	Simapro
Electric radiators	steel and alkyd paint (40kg)	[72], [73], [74], [75]
Floor heating		
Piping (OD=17mm, t=2mm)	PE (170m)	Simapro

TABLE 3.7: Individual heating system - Emission part

3.4.2 Collective Heating System

After modelling the individual heating systems (IHSs), the collective heating system (CHS) can be modelled. It can again can be subdivided into three parts: a generation part, distribution part and an individual part. The individual part of each building, is similar to the previously determined IHSs, apart from the generation unit, which is now replaced by the collective generation and distribution part. An overview of the CHS from 'De Schipjes' was depicted in figure 3.2. Below, a breakdown of each part will be given.

Collective System - Generation Part

The heat is generated by two independent generation units: A GSHP with a vertical bore field and a solar thermal collector (STC). The heat of both units is conveyed to a separate 950 l buffer tank, disconnecting the generation from the distribution, and improving the system's performance. A representation of the generation part can be found in appendix B.2 and an overview of all the components of each unit and their decomposition is given in table 3.8.

The vertical bore field comprises 8 boreholes, each with a depth of 125 m and a width of 20 cm. Each borehole is modelled similarly to the one in the individual scenario. The heat extraction from these boreholes is facilitated through double U-tubes made from PE, featuring an outer diameter of 32 mm and a thickness of 2.3 mm. After placing the tubes, the holes are filled with a grouting material. For structural stability, spacers are placed for each U-tube, every three meters. The heat transfer fluid employed in the bore field is again a mixture of water and 25% glycol. The GSHP, upgrading the heat from the bore field, is modelled through a mass-based extrapolation of the same predefined generic GSHP from Simapro. The component is based on a datasheet from *Viesmann*, with a nominal heating power of 42kW and a mass of 298 kg. The employed refrigerant is 7.7kg R134a. A circulation pump of 150 W ensures a good circulation of the fluid through both the bore field and the GSHP. For control and monitoring purposes, several control valves and pressure and temperature sensors are placed at each borehole and at the HP. An expansion vessel of 50l guarantees an acceptable pressure level in the pipes.

The STC, assists the bore field on sunny days. For the model, a predefined component from Simapro is used, which is modelled per m^2. In the collective scenario, a flat plate STC with a copper absorber covers an area of 14 m^2. Further, a circulation pump is used for the circulation of the water mixture with 25% glycol. for similar reasons as before, an expansion vessel, control valve and pressure and temperature sensors are included. For modelling reasons, the network after the heat pump and STC are defined in the distribution part. From the additional components, only the circulation pumps of the bore field and the STC are still modelled with the generation part. The valves, sensors and pipes (apart from the double U-tubes) belong to the distribution part.

Component	**Material**	**Source**
GSHP (42 kW)	Metals and plastics (320 kg)	Viessmann/Simapro
Refrigerant	R134a (7.7 kg)	Viessmann/Simapro
Vertical bore field	8 boreholes (125 m)	
Drilling (D = 200 mm)	Soil (8*125 m)	Simapro
U-tubes (D = 32 mm, t = 3.2 mm)	PE (8*4*125 m)	Simapro
Grout (33/33/33 mass%)	Cement/bentonite/silica (28.2 m^3)	*Boringen Verheyden* and [42]
Expansion vessel (2 x 50 l)	Steel (2 x 12 kg)	Simapro
Circulation pump (150 W)	Metals and plastics (4.2 kg)	Simapro
Liquid	Water-glycol 25% (3 763 kg)	Simapro
Spacers	PE (666 pieces)	Simapro
STC	Metal (14 m^2)	Simapro
Expansion vessel (25 l)	Steel (4.5 kg)	Simapro
Circulation pump (30 W)	Metals and plastics (2.0 kg)	Simapro

Table 3.8: Collective heating system - Generation part

Distribution Part

After extraction, the heat is stored in two 950 l storage tanks, separating the distribution from the generation. The heat transfer fluid after the GSHP, in the two storage tanks and in the rest of the distribution part, is demineralized water (RO water). The LCA data of the RO water is obtained from research done by the private company *Water Without Waste*. The placement of the piping network, was modelled based on information from *Mirom*. The lines are placed in a trench at a depth of 0.8 m and a width of 0.8 m. The supply line (hot water) is connected to the water tank from the GSHP and the return line (cold water) is connected to the tank from the STC, serving as a preheater. The supply temperature is 50°C and the return temperature is 40°C. When there is a heat demand in one of the buildings, the pump of the distribution network, with a nominal power of 400 W, is activated, utilizing the heat stored in the tank connected to the GSHP. Once the temperature in this tank drops below a predefined threshold (46°C), the GSHP is activated. The STC remains active as long as the temperature in the preheating tank is below a certain threshold. Subsequently, the hot water is transferred through a network of pipes with varying diameters to the buildings. A more detailed description of the piping network can be found in table 3.9. An expansion vessel of 50 l, several control valves and temperature and pressure sensors ensure a smooth distribution of the heat.

Component	**Material**	**Source**
Storage tank (950 l)	Metals and plastics (151 kg)	Simapro
Expansion vessel (25 l)	Metals and plastics (4.5 kg)	Simapro
Circulation pump (100 W)	Metals and plastics (2.4 kg)	Simapro
Piping network		
Pipe (OD = 90 mm, t = 65 mm)	Steel-PUR-HDPE (15 m)	Simapro
Pipe (OD = 90 mm, t = 70 mm)	Steel-PUR-HDPE (32 m)	Simapro
Pipe (OD = 110 mm, t = 70 mm)	Steel-PUR-HDPE (25 m)	Simapro
Pipe (OD = 110 mm, t = 78 mm)	Steel-PUR-HDPE (14 m)	Simapro
Pipe (OD = 125 mm, t = 75 mm)	Steel-PUR-HDPE (62 m)	Simapro
Pipe (OD = 140 mm, t = 75 mm)	Steel-PUR-HDPE (26 m)	Simapro
Excavation process	Soil (0.8*0.8*174 m^3)	Simapro and *Mirom*
Expansion vessel (50 l)	Steel (12 kg)	Simapro
Circulation pump (400 W)	Metals and plastics (5 kg)	Simapro
Liquid	RO water (433 kg)	*Water Without Waste*
Control valves	Metals and plastics (20 pieces)	
Sensors (P en T)	Metals and plastics (18 pieces)	

TABLE 3.9: Collective heating system - Distribution part

Individual Part

The individual part for each building, can again be subdivided into a heat generation part, heat distribution part and heat emission part, from which the latter two have already been described in the section about the individual scenarios 3.4.1.

The individual heat generation or rather heat extraction and generation part in the collective scenario utilizes the heat from the collective distribution network. The heat is extracted from the network through a 9kW heat exchanger. This heat is then transferred both to the central heating system and to the booster heat pump with a heating power of 2kW, for domestic hot water (DHW). In the model, the component for the BHP is based on a datasheet from *Ithodaalderop* and is implemented again via a mass-based extrapolation of the same predefined GSHP from Simapro. The supply temperature is 45°C and the return line has a temperature of 35°C. The hot water for central heating is then conveyed to the site of emission, which consists of floor heating and radiators. The booster heat pump upgrades the heat coming from the heat exchanger to a temperature of 55°C. Every few days, a legionella disinfection of the water tank is performed, reaching temperatures up to 70°C. The hot water for DHW is stored in a 90 l tank. If the temperature of the water drops below 50°C, the BHP is activated. The BHP also compromises a preheater, which can preheat the colder water from the storage tanks, before entering the condenser of the heat pump, improving its efficiency. The temperature of the water entering the evaporator is limited to 40°C. The new components of the individual part are listed in table 3.10. The central heating network and emission units are the same from the individual scenario (table 3.6 and 3.7).

Component	**Material**	**Source**
Heat exchanger (9 kW)	Chromium steel (2.25 kg)	Simapro
BHP (2 kW)	Metals and plastics (38 kg)	Simapro
Water tank (90 l)	Metals and plastics (26 kg)	Simapro
Piping (OD = 90 mm, t = 65 mm)	Steel - PUR - HDPE (6.785 m)	
Sensors (P en T)	Metals and plastics (8 pieces)	Simapro
Control valves	Metals and plastics (5 pieces)	Simapro
Central heating network		
Emission units		

Table 3.10: Collective heating system - Individual part

3.5 Operational Energy Use

Apart from the materials, also the energy use is included in the assessment. In this section, the operational energy use will be discussed, which consists of the energy used for central heating (CH) and domestic hot water (DHW). Typically, when the environmental impact of a system is analyzed, only the operational CO_2 emissions from the system are considered. Here, other environmental impact indicators are integrated as well. In the scenario of the gas boiler, natural gas is the primary energy source. Ecoinvent has no record of natural gas from a low-pressure distribution grid in Belgium, but it does offer a Swiss variant. The gas utilized in the analysis is modeled after its Swiss counterpart, with adjustments made to reflect Belgian processes instead of the Swiss ones [5].

The electric boiler, heat pumps, circulation pumps ventilation unit, etc., utilize electricity as an energy source. In contrast to natural gas, Ecoinvent does have a Belgian, low-voltage electricity mix from 2016 [5]. More detailed information on the electricity mix can be found in table 3.11 This electricity mix has a lower environmental impact than the current mix, which will probably get even worse in the near future due to decommissioning of nuclear power plants. To get a better idea of the impact of the evolving electricity mix on the environment and its influence on the footprint of heating systems, greener electricity mixes will be considered as well later in this study. Also, a dynamic and a static electricity mix will be compared.

In TOTEM, the operational energy use for heating is calculated via the Equivalent Heating Degree Days method (EHDD), in which only the transmission and ventilation losses are considered. The yearly environmental impact of the energy, used for heating is estimated via formula 3.1 [5]. The energy use for DHW is estimated based on the formula 3.3.

$$E_{CH} = \frac{U_m * S + V * n_{tot} * 0.36}{\eta_p * \eta_d * \eta_e * \eta_c} * DD_{eq} \tag{3.1}$$

In this formula, U_m $[W/m^2K]$ denotes the average heat transfer coefficient, S $[m^2]$ the heat loss surface of the building, V the heated volume $[m^3]$ and $n_{tot} = n_{vent} + n_{inf}$ $[h^{-1}]$ the sum of the ventilation and infiltration per hour. A default air infiltration rate of $12m^3/hm^2$ is assumed. the term DD_{eq} [°s] stands for the equivalent degree-days, which is 1200 [°D], multiplied with $(24 * 60 * 60/10^6)$ to convert days into seconds and joules into megajoules. The values in table 3.13 for the efficiencies of distribution (η_d), emission (η_e) and control

Type	**Share (2016)**
Gross Production	**84.1%**
Coal	0.33%
Gas	20.87%
Oil	0.01%
Nuclear	44.50%
Hydro	1.60%
Onshore wind	3.51%
Offshore wind	2.31%
Solar	5.83%
Biomass	5.09%
Import	**15.9%**
France	5.21%
The Netherlands	10.72%

Table 3.11: Belgian electricity mix (2016) based on ecoinvent (version 3.6)

Component	η_d	η_e	η_c
Radiators and floor heating	0.95	0.96	0.92
Electric heating	1	0.925	0.95
Collective network	0.9	-	-

Table 3.12: Distribution, emission and control efficiencies proposed by VEA 2013 [16]

(η_c) are proposed by the Flemish Energy Agency (VEA 2013) [16] [5]. The production efficiency (η_p) or COP is scenario dependent and is given in table 3.8. for the collective scenario, an extra efficiency has to be included, to account for the losses in the storage tanks and collective distribution network. This collective distribution efficiency is estimated as $\eta_{d,c} = \frac{Q_{gshp}+Q_{stc}-Q_{loss}}{Q_{gshp}+Q_{stc}} = 0.85$. However, in these calculations, the advantage of the STC supplying what is essentially 'free' heat, is not accounted for. Therefore, a correction factor $\left(f = \frac{Q_{gshp}+Q_{stc}+Q_{bhp}}{Q_{gshp}+Q_{bhp}} = 1.06\right)$ was defined, to simulate the fact that the heat provided by the STC does not require any electricity use, apart from the circulation pump, which is almost negligible. This lead to $\eta_{d,c} * f = 0.9$, which is similar to the value proposed by the Flemish Energy Agency. For this estimation, the values from table 3.15 were used, determined by the Rule-Based Control (RBC)) simulation, which will be discussed below. The energy use for DHW is calculated as follows:

$$E_{DHW} = \frac{C_{HW} * (T_{HW} - T_{CW}) * 4.186 * 365 * 10^{-3} * N}{\eta_{p,dhw}} + Q_{storage\ loss} \tag{3.2}$$

Component	$\eta_{p,dhw}$
Condensing gas boiler	0.85
Electric heating	1
Heat pump	1.4

Table 3.13: Production efficiency DHW proposed by VEA 2013 [16]

Where C_{HW} [l/person/day] denotes the consumption of domestic hot water, estimated to be 25 l/person/day. T_{HW} and T_{CW} [°C] are the temperature of the hot and cold water, which are by default set at 60°C and 10°C. N represents the number of inhabitants and $Q_{storage\ loss}$ denotes the yearly heat loss during storage [15] [16]. The total operational energy use is the sum of the required energy for both CH and hot water. For standardization purposes and because Joule is the SI standard, the final energy use is expressed in MJ [1]. According to the guidelines set by the Flemish Energy Agency, storage heat loss must be considered for scenarios involving gas boilers and electric heating systems. For storage units with a capacity of less than 100 liters, typical of individual scenarios, the heat loss is 595 MJ. For storage capacities ranging from 100 to 200 liters, relevant to the Totem reference scenario, the heat loss is 1710 MJ. The production efficiencies for DHW ($\eta_{p,dhw}$)are as follows: 0.85 for gas boilers, 1 for electric boilers, and 1.4 for heat pumps.

$$E_{op} = E_{CH} + E_{DHW} \tag{3.3}$$

In this study, a dynamic approach is implemented as well, in which the operational energy use is based on simulation data from a modelica model of the collective heating system based on rule-based control (RBC) [76]. In this model, the heat generation of the bore field with the GSHP, the STC, as well as the BHP, is simulated. Apart from the generated heat, also the heat losses from the distribution network are simulated. After determining the heat generation, the electricity use of each unit can be calculated by dividing by their COP. The COP for each ASHP and GSHP has been determined as 3 and 4 respectively, according to their datasheets, see appendix A. The vertical and horizontal bore fields are treated as one in the energy calculations and are considered to have the same COP. In reality, the COP of the vertical bore field might be slightly higher due to better thermal stability. The STC does not require any electricity apart from the circulation pump. The electricity use of each circulation pump in the system was estimated by considering them operating at nominal power when their corresponding heat generation unit is active. The electricity use of the collective scenario ($E_{tot,col}$) can then be calculated by summing up the collective ($P_{col,col}$) and the individual ($P_{col,ind}$) energy use of each building, integrated over one year. For the model, the electricity usage per building is determined by dividing the shared electricity usage of the collective part by 12. The energy use is again converted from Wh to MJ and divided through the UFA, to determine the energy use per UFA. Because of limited information on the distribution of the heat flows, no distinction between heating and DHW was made during these calculations.

$$P_{col,col} = \frac{\dot{Q}_{gshp}}{COP_{gshp}} + P_{pump,bf} + P_{pump,gshp} + P_{pump,stc} + P_{pump,distr} \tag{3.4}$$

$$P_{col,ind} = \frac{\dot{Q}_{bhp}}{COP_{bhp}} + P_{pump,bhp} \tag{3.5}$$

$$E_{tot,col} = \int_0^{1year} (P_{col,col}/12 + P_{col,ind})\, dt * 3.6 * 10^{-6} \tag{3.6}$$

Now the energy use of the individual scenarios can be estimated, as demonstrated in formula 3.7. The total energy use will be lower, because of avoided heat losses in the

---

[1] 1 kWh = 3.6 MJ

distribution network. The final electricity or gas usage for each of the individual scenarios can be estimated by dividing through the efficiency of the boiler or electric heating, or through the COP of its heat pump. For modelling purposes, the energy use is converted again to MJ per m^2 UFA. This means for the collective system, it is divided by 600 m^2, which 12 times the UFA of a building. The resulting energy use, efficiency and COP of each generation unit is listed in table 3.14. For each scenario, the electricity use of all components, except the circulation pumps of the internal system is accounted for. The efficiency of the gas boiler is based on a predefined value in the MMG tool, retrieved from the flemish directions [16], while the efficiencies of the electric boiler, electric radiator and heat pumps are obtained from their respective datasheets: [72], [73], [73], [75] and see appendix A for the data sheets of the heat pumps.

$$Q_{tot,ind} = \int_0^{1\ year} \left([\dot{Q}_{gshp} + \dot{Q}_{stc} - \dot{Q}_{col,loss}]/12 + \dot{Q}_{bhp} \right) dt * 3.6 * 10^{-6} \tag{3.7}$$

$$E_{gas\ boiler} = \frac{Q_{tot,ind}}{\eta_{gas\ boiler}} \tag{3.8}$$

$$E_{electric\ heating} = \frac{Q_{tot,ind}}{\eta_{electric\ boiler}} \tag{3.9}$$

$$E_{ashp} = \frac{Q_{tot,ind}}{COP_{ashp}} \tag{3.10}$$

$$E_{gshp} = \frac{Q_{tot,ind}}{COP_{gshp}} + E_{pump,bf} \tag{3.11}$$

Scenario	**Energy use** $[MJ/m^2]$	**Efficiency** [%] **or COP**[-]
Individual - Gas boiler	605 (gas)	90%
Individual - Electric boiler/radiator	550 (electricity)	99%
Individual - ASHP	181 (electricity)	3
Individual - GSHP	136 (electricity)	4
Collective	164 (electricity)	4

TABLE 3.14: Energy use, and efficiency or COP for each scenario

From these calculations, the profiles of daily energy use can be determined, depicted in figures 3.6 and 3.6 below. The energy use is much lower for scenarios featuring a HP. The difference lies in the selected COP and the distribution losses for the collective scenario. The gas boiler and electric heating have substantially larger energy use.

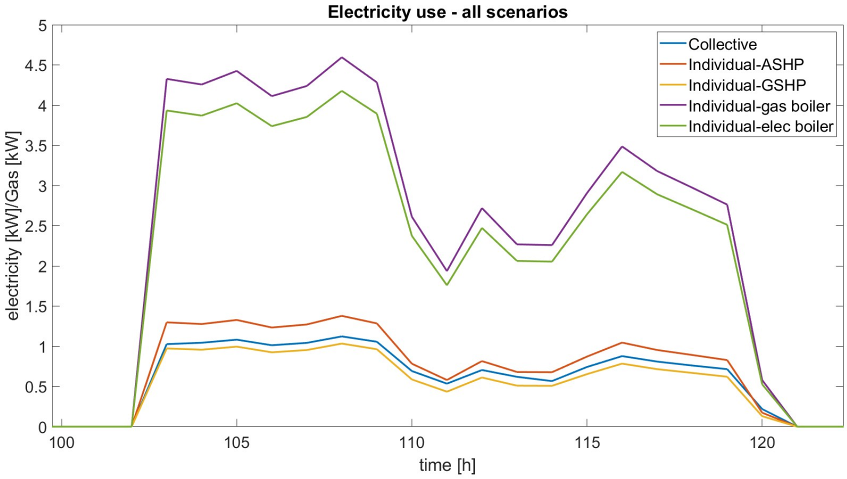


FIGURE 3.5: Energy use profile of one day in winter

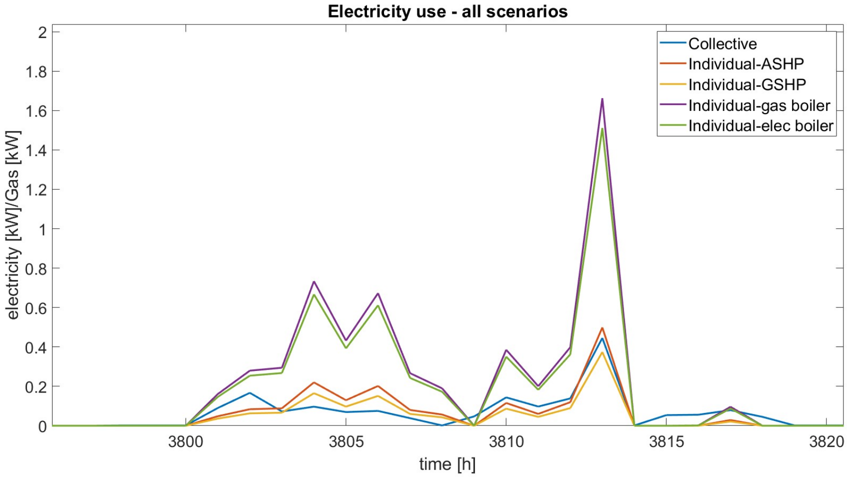


FIGURE 3.6: Energy use profile of one day in summer

To get a better idea of the generated heat of each generation unit in the collective system, the generated heat for each unit is given in table 3.15. The highest heating power in the simulation of the collective scenario, was calculated to be 4.4kW. Therefore, a required heating power of 5 to 6 kW was assumed during the modelling of the emission units in previous section. The generation units are slightly over dimensioned, with a nominal heating power of 9 and 9.7 kW for the ASHP and GSHP respectively. As expected is the collective GSHP responsible for the largest part of the heat generation. The STC on the other hand, only generates a small amount of heat. The generated heat by the BHP of 50.00 GJ in the table, is the total heat generation of all 12 BHPs. The distribution loss of almost 55.70 GJ is 17.4% of the collectively generated heat and will contribute significantly to the environmental impact of the collective scenario.

Generation unit	**Generated heat [GJ]**
GSHP	298.30
STC	22.66
BHP	50.00
Distribution Loss	55.70

TABLE 3.15: Generated heat collective system

3.6 Conclusion

In this chapter, the models for the different scenarios were worked out. In a first step, the buildings were modelled based on a use case *De Schipjes*. For this, some materials in the building elements were substituted with similar available materials due to lacking data in the database. Once the building layout was defined, the technical installations for various scenarios were modeled. These included a gas boiler, an electric boiler and electric radiators, an ASHP, a GSHP with a vertical bore field, and a GSHP with a horizontal bore field. Conflicting data from datasheets of several technical installations led to the selection of generic components from the Simapro database. Radiators were implemented for heat emission in the case of a gas boiler, while radiators were combined with floor heating for heat pump scenarios. In the scenario with electric heating, an electric boiler was combined with electric radiators for DHW and central heating respectively. Finally, the collective system was modelled, comprising a GSHP with a bore field, an STC, a distribution network with two 950l storage tanks, and a heat exchanger with BHP at each building to transfer and upgrade the collective heat. Apart from materials, operational energy use was estimated via two methods: EHDD and a dynamic method based on RBC.

Chapter 4

Results and Discussion

Once the various scenarios have been modelled using the MMG KU Leuven tool, the environmental impact of both individual and collective heating systems can be evaluated. The EHDD method will be utilized for the initial assessment of operational energy usage. Following this, the assessment will be reviewed using the RBC method. With these assessments, a first attempt will be made to answer the research questions. Because the dwellings in the use case are rather small with a UFA of $50m^2$ and a heated volume of 131 m^3, a scenario from Totem was modelled as well as a reference. The Totem model consists of a building with a UFA of 150 m^2, a heated volume of 525 m^3 and a gas boiler as heat source. Generally, larger dwellings have an advantage compared to smaller dwellings, as the environmental impact of technical installations per square meter is usually lower. This is because material use does not scale linearly with the nominal power of the installation, resulting in a lower mass per unit of nominal power. Additionally, the energy use per square meter is also reduced, as it does not scale linearly with the UFA of the building. These considerations will be further elaborated upon in the discussion of the results.

4.1 Assessment Heating Systems - EHDD Method

The evaluation of various scenarios will be carried out from three perspectives. Initially, the impact will be divided into materials and energy usage. Secondly, the impact will be distributed across different stages of the life cycle. Finally, the contribution of various impact indicators will be examined. Here the energy use will be calculated using the EHDD method, in the next section the RBC-based method will be discussed.

4.1.1 Materials and Energy Use

In figure 4.1, the environmental impact of the materials and energy use for each scenario is depicted. Each scenario from the use case is modeled with the same building envelope. The building elements are integrated into the assessment to provide a comprehensive view of the total impact of buildings. The differences in environmental impact are only due to the heating part of the technical installations and their energy use. It is important to note that scenarios involving a heat pump are modeled based on a mass extrapolation of a generic component, using LCA data from Simapro. This carries two significant implications. Firstly, the nominal power of the ASHP and GSHP are 9.7kW and 9kW respectively, exceeding the required 5 to 6 kW that determined during the energy use calculations in section 3.5. Secondly, these generic components typically represent worst-in-class performance, implying that the environmental impact of these scenarios is likely overestimated. Scenarios with other heat pumps will be modelled as well in section 5.1.

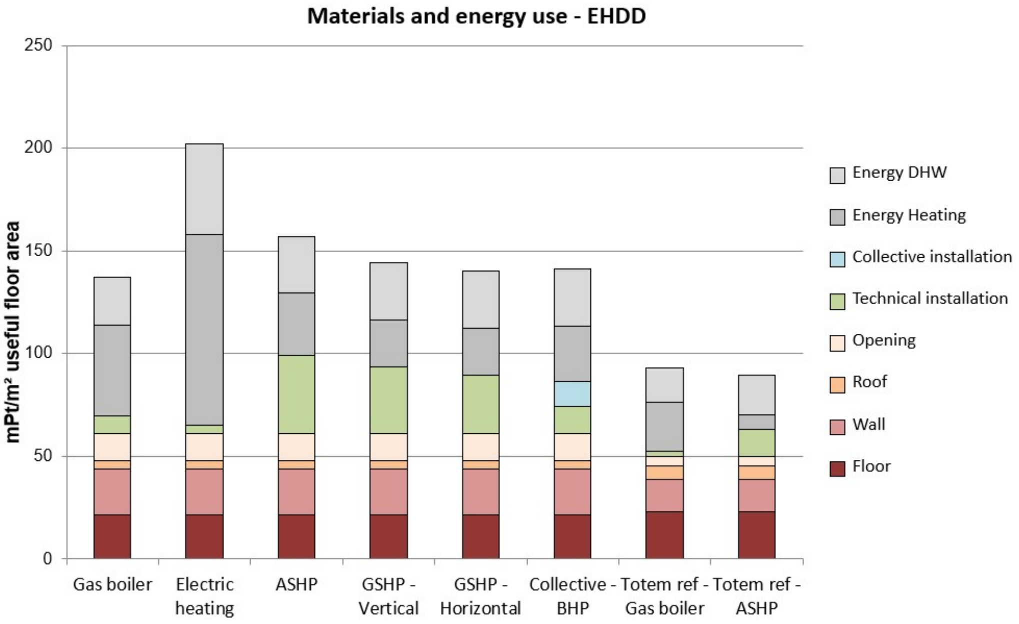


FIGURE 4.1: Materials and energy use (EHDD)

From the figures is clear, that the heat pump scenarios have a higher or similar environmental impact compared to the gas boiler. The gas boiler has the lowest impact of 137 mPt/m^2, while electric heating is the worst in class with an impact of 202 mPt/m^2. The ASHP exhibits a lower impact with 157 mPt/m^2. The GSHP scenarios perform even better, with impacts of 144 mPt/m^2 for the vertical bore field and 140 mPt/m^2 for the horizontal bore field. The reference models from Totem, with a UFA of 150 m^2, highlight the effect of building size. Both the impact of material use and energy use per m^2 decrease for larger buildings. For the material use, this decrease is larger, partly because identical heating installations had to be implemented for the use case and the TOTEM reference scenario. This highlights the importance of the energy use and the selected heating installation. For the larger dwellings, the energy use becomes more important, leading to the HP scenario surpassing the scenario with a gas boiler. This also shows, that the conclusions drawn from the assessment of this use case can not be extrapolated to larger buildings. But, due to the increasing importance of the energy use for larger buildings, the scenarios with a more efficient energy use, such as heat pumps but also collective heating systems, would benefit from this.

As expected, the technical installation of the boiler and electric heating have significantly lower impacts regarding material use. The high impact of the material use of the heat pump installations shows the importance of the selected heat pump model. A different weight or different LCA data might have a significant effect on the environmental impact on the results and might shift the order. This will be investigated further in the next chapter. As expected, the reference models from totem exhibit a lower impact (93 mPt/m^2 and 77 mPt/m^2) than the models from the use case, mainly caused by the larger UFA. Interestingly, the heat pump performs better than the gas boiler for larger dwellings. Instead of determining the environmental impact per m^2 UFA, another interesting approach could be taken, in which the environmental impact is determined per resident. Assuming that the use case has two residents per building and the Totem reference model has four, the model from use case with a gas boiler (3425 mPt/resident) ends up outperforming its reference model (3925 mPt/resident). However, the reference model with an ASHP (2888 mPt/resident) is still better off than the use case (3488 mPt/resident).

$$EI_{use\ case,\ gas\ boiler} = \frac{137\ mPt/m^2 * 50\ m^2}{2\ residents} = 3425\ mPt/resident \tag{4.1}$$

$$EI_{use\ case,\ ashp} = \frac{157\ mPt/m^2 * 50\ m^2}{2\ residents} = 3925\ mPt/resident \tag{4.2}$$

$$EI_{Totem\ ref,\ gas\ boiler} = \frac{228\ mPt/m^2 * 150\ m^2}{4\ residents} = 3488\ mPt/resident \tag{4.3}$$

$$EI_{Totem\ ref,\ ahsp} = \frac{77\ mPt/m^2 * 150\ m^2}{4\ residents} = 2888\ mPt/resident \tag{4.4}$$

The distribution of energy use between domestic hot water (DHW) and central heating (CH) is approximately 30/70 for gas boilers and electric heating and 50/50 for heat pumps. The higher impact of DHW for heat pumps is due to the lower COP for DHW, because higher temperatures are required compared to CH. For gas boilers and electric heating the same efficiencies are used for both DHW and CH. The impact of the total energy usage is lower for the heat pumps, which aligns with expectations. However, upon calculating the energy usage, it was found that the energy use of the electric heating (309 MJ/m^2) was below the energy use of the gas boiler (342 MJ/m^2). Surprisingly, despite this, the environmental impact of energy use appears higher for the electric heating scenario. This suggests that the environmental impact of one MJ of the electricity mix is higher than one MJ of natural gas. This is supported by figure 4.2, displaying the contribution of the different impact indicators of one GJ of electricity and natural gas. Mainly the depletion of fossil fuels causes the impact of the electricity use to be high. This emphasizes the importance of integrating more renewable sources into the electricity mix.

When comparing the various heat pump scenarios, the impact of the ASHP appears to be greater than that of the GSHPs and their bore fields. This discrepancy could stem from two main reasons. Firstly, an ASHP typically requires a larger size and an additional outdoor unit. But a GSHP necessitates the construction of a bore field, which is generally quite invasive. Apparently, the impact of the additional units outweighs the construction of the bore field in this case. However, there's a considerable disparity between the two heat pump models. The ASHP model, with a mass of 205kg, is substantially heavier than the GSHP model, which weighs only 129kg, resulting in a significantly higher impact. Because there is no additional information about the source of this data, no further elaboration could be done. In the next chapter, different heat pumps will be compared based on several data sources, which might bring more insight. Further, it is important to note that the same energy usage was applied to the two scenarios with a GSHP. In reality, the COP of the vertical bore field is slightly higher due to more stable and elevated ground temperatures, resulting in lower energy use. Since energy use appears to be the determining factor for environmental impact, this could alter the conclusion.

Now, the collective heating system can be compared to the individual scenarios. The concept of a collective heating system involves replacing individual heat pumps with a central

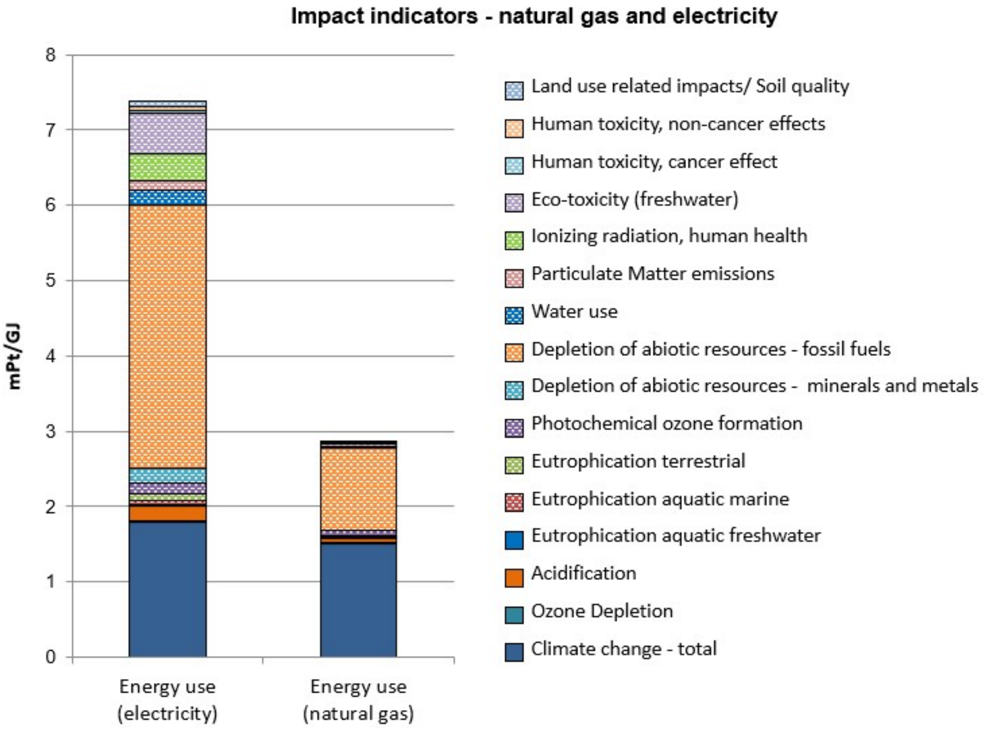


Figure 4.2: Impact indicators natural gas and electricity

unit and a distribution network, with the aim of distributing the cost and environmental impact of the system among its users, potentially reducing the energy use, the cost and the environmental impact. If necessary, this heat can be upgraded locally by a smaller booster unit. Interestingly, the collective heating system slightly outperforms the individual scenario with a GSHP and a vertical bore field, with an impact of 141 mPt/m^2. The individual scenario with a GSHP and horizontal bore field, and the individual scenario with a gas boiler perform slightly better. The impact of the technical installations is distributed fairly similar between the collective and individual parts. Similar to the GSHP with a vertical bore field, the GSHP in the collective scenario is likely to have a higher COP than the GSHP with a horizontal bore field. Furthermore, a possible synergy with the STCs, such as regeneration of the bore field during hot summer months, and the flexibility introduced by the storage tanks might contribute to improved performance once again. Combined, all these elements above can improve the performance of the collective heating system, reducing its energy use and resulting in a lower environmental impact. Given the current small difference between collective and individual heating systems, the collective system might end up having the lowest overall impact, proving its potential. In the next section, energy usage will be calculated based on the RBC method, which might offer more insights.

Technical Installations

A closer look is taken at the environmental impact of the materials from the technical installations. In figure 4.3, the generation part seems to be responsible for the biggest part of the impact of the installations. For a better understanding of the distribution inside the technical installation of the GSHP, the impact of each component of the GSHP with a vertical bore field is shown in figure 4.4. It becomes clear, that the heat pump itself has the highest impact, followed by the bore field and the radiators. The impact of the floor heating appears to be lower than the radiators, by comparing the emission system of the gas boiler with the heat pumps. Note that the environmental impact is given per functional unit instead of UFA. The system with an electric boiler and electric radiator has the lowest impact. As mentioned before, the impact of the ASHP is higher because of the corresponding heavier generic model. The key distinction between the two GSHPs lies in the bore field. The impact of the horizontal bore field appears to be lower than that of the vertical bore field. This variance could be attributed to the use of grouting material in the vertical bore field, which was not utilized in the horizontal bore field. Also, the effect of the different emission units can be observed, by comparing the impacts of the scenario with a gas boiler and the scenario's with a HP. The gas and electric boilers use radiators, in contrast to the heat scenario, where both floor heating and radiators are employed. According to the results, the impact of the floor heating is lower than the impact of the radiators. The high impact of the radiators can be attributed to the large amount of metals used in their construction. It must be noted, that in these scenarios only a simple version of the floor heating was modelled. The floor heating tubes were embedded in the cement screed. Other floor heating models, place the pipes in a metal grid or on positioning mats, which might have a higher impact.

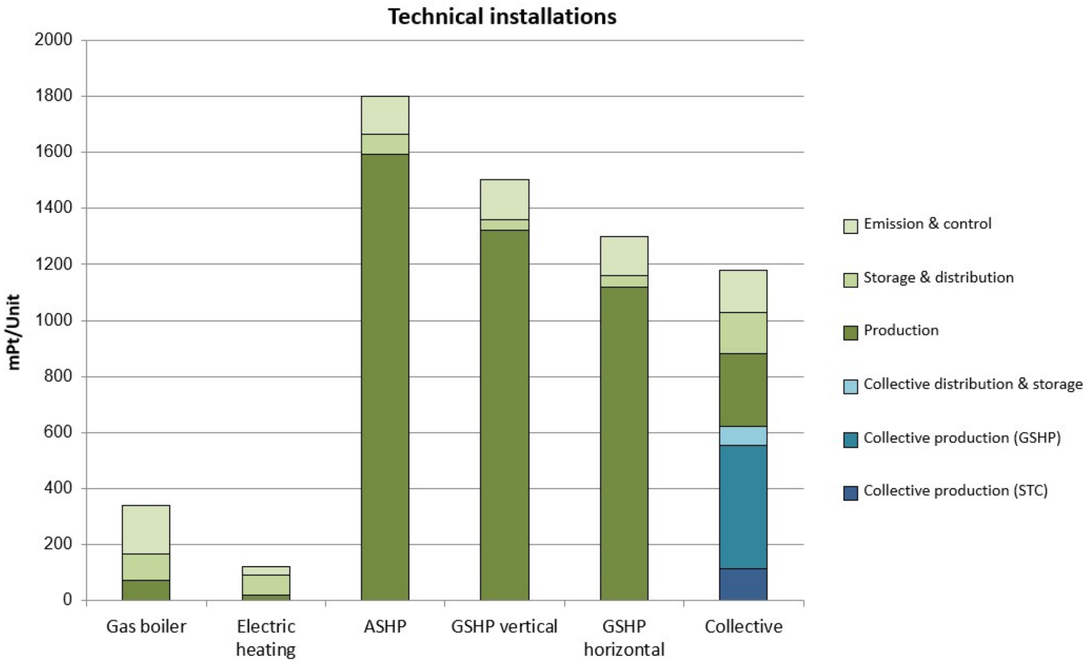


Figure 4.3: Technical installations

Figure 4.3 confirms the core idea behind the collective heating system. By distributing the material and installation impacts of a central system across multiple users, the collective approach effectively reduces the overall impact of the installation. Also in the collective system, the heat generation units seem to be responsible for the biggest impact. Interestingly, the collective distribution and storage seem to have a low impact. This finding is intriguing because it suggests a potential for utilizing waste heat from industries as a heat source. Since this waste heat is essentially 'free', the large impact of the generation unit is minimized or even eliminated entirely, leaving only the distribution aspect to consider. While the distribution network may be substantially larger, its environmental impact could still be lower than that of a GSHP with a bore field and STC.

The impact of the collective GSHP and bore field (440 mPt) is much higher than the STC (113 mPt), but in comparison to the generated heat, the GSHP (188 kWh/mPt) proves to be much better than the STC (123 kWh/mPt). If this is the case, the collective system is better off without the STC. However, the STC is also used to regenerate the bore field during hot summer months. Without the STC, the required bore field size would be larger, leading to a higher impact on this side. Also, the STCs do not require any electricity apart from the circulation pump for the heat generation. In reality, a trade-off has to be found in which the impact of the total heat generation part is minimized.

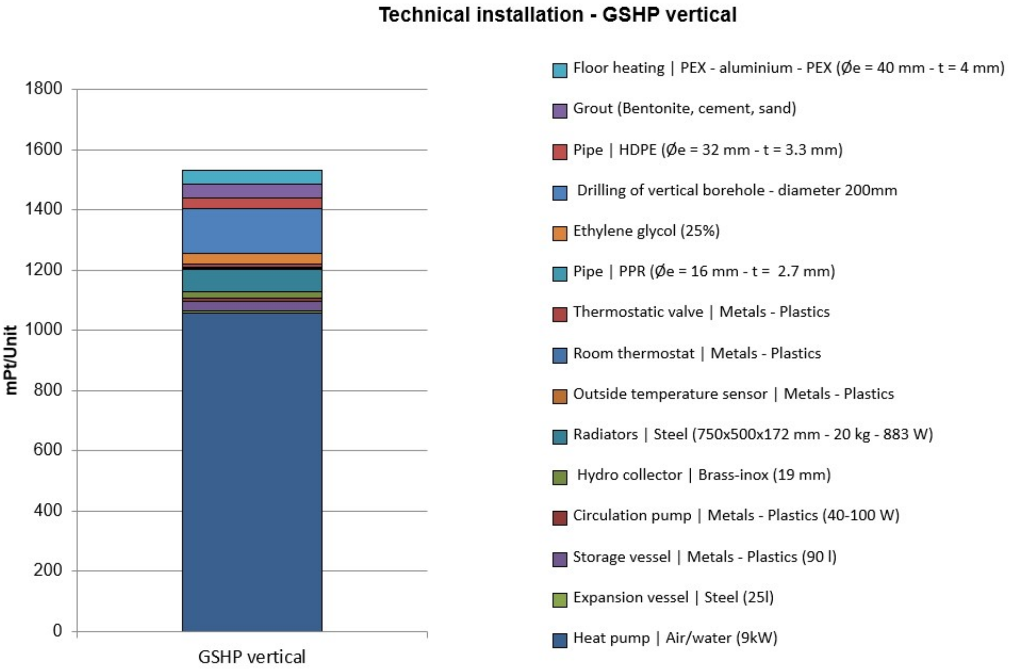


FIGURE 4.4: Environmental impact of each component of the GSHP

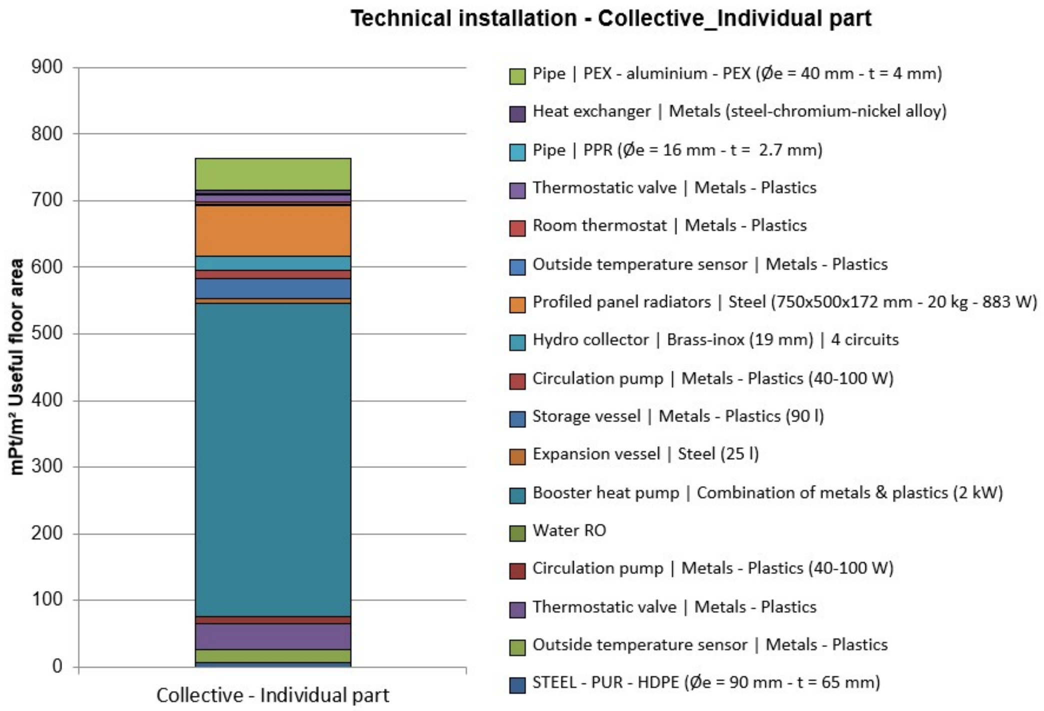


FIGURE 4.5: Environmental impact - individual part of the collective scenario

Apart from the collective generation and distribution part, also the individual storage and distribution setup in the collective scenario differs from that of the individual scenarios. It requires a heat exchanger, valves, sensors, and additional pipelines to facilitate the transfer of heat from the collective distribution to the BHP of the buildings. The impact of the different components in this individual part is represented in figure 4.5, from which the BHP is again the most dominant. The sole purpose of this BHP is to generate DHW. If this component would be replaced by an electric boiler, the impact of the technical installation could be reduced significantly. But the energy use will increase again. From figure 4.6 is clear that the impact of the technical installation is indeed reduced. However, the increase in energy use outweighs this reduction, concluding that the BHP is currently the better option for the collective scenario.

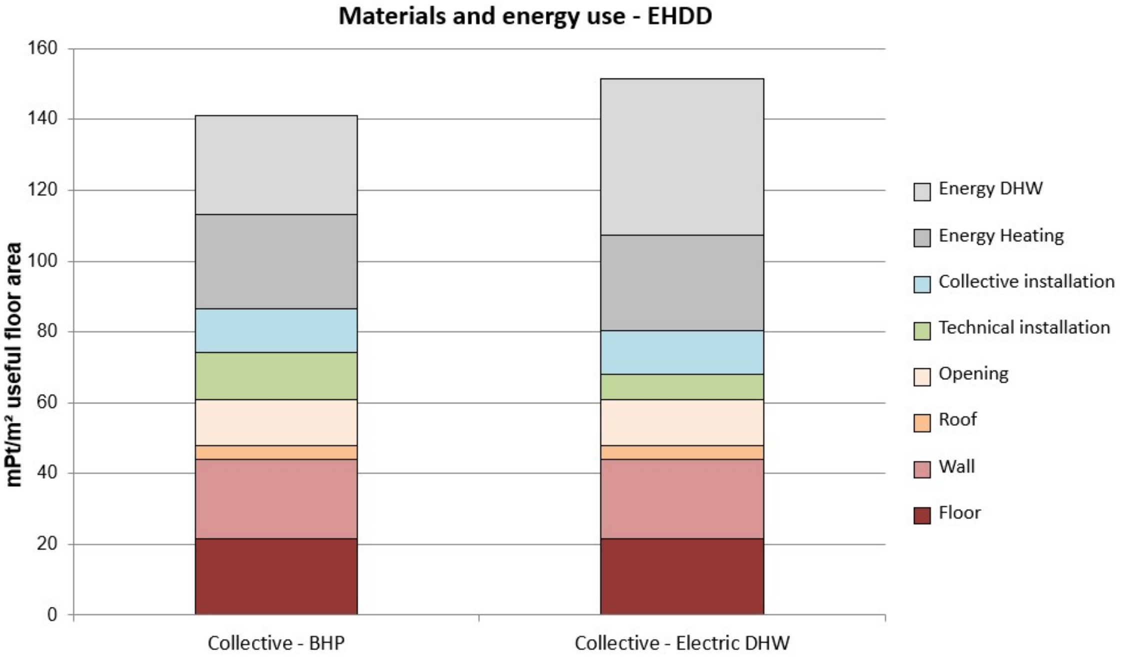


Figure 4.6: Collective scenario - BHP VS Electric boiler

4.1.2 Life Cycle Stages

In an LCA, the environmental impact of a component is determined, by aggregating over all life cycle stages. From figure 4.7 is clear, that the impact is concentrated in a few modules, i.e. the product stage (A1-A3), the replacement (B4) and the operational energy use (B6). The impact of cleaning and maintenance is primarily determined by the refrigerant refilling. For the scenarios involving a heat pump, a yearly leakage of the refrigerant of 2% was considered, which is refilled during maintenance. This 2% is based on the value used in the MMG KU Leuven tool and was verified by most of the datasheets, which can be found in appendix A. These leakages only occur due to installation errors. If the heat pump installation is done by specialists, this leakage might be eliminated. In the MMG KU Leuven tool, a building lifetime of 60 years is considered. Most of the building elements, including the floors, walls, roof, windows and doors, but also the bore fields and piping networks are expected to have a service life of 60 years or more. The technical installations have a life expectancy that is lower. Both the boiler and the heat pump in these scenarios are modelled with a life expectancy of 20 years and require replacement twice during the 60-year period. This leads to a significant impact, which is represented in the replacement phase (B4). The higher material impact of the HP during the construction phase will also extend into the replacement phase. The operational energy use dominates the environmental impact and has already been discussed in section 4.1.1 about materials and energy.

4.1.3 Environmental Impact Indicators

As mentioned in the introduction, environmental impact assessments of systems often rely on operational CO_2 emissions as a metric. However, other environmental damages also occur, reflected in LCAs through multiple impact indicators. The total climate change seems to represent only a fraction of the total environmental impact. Only considering

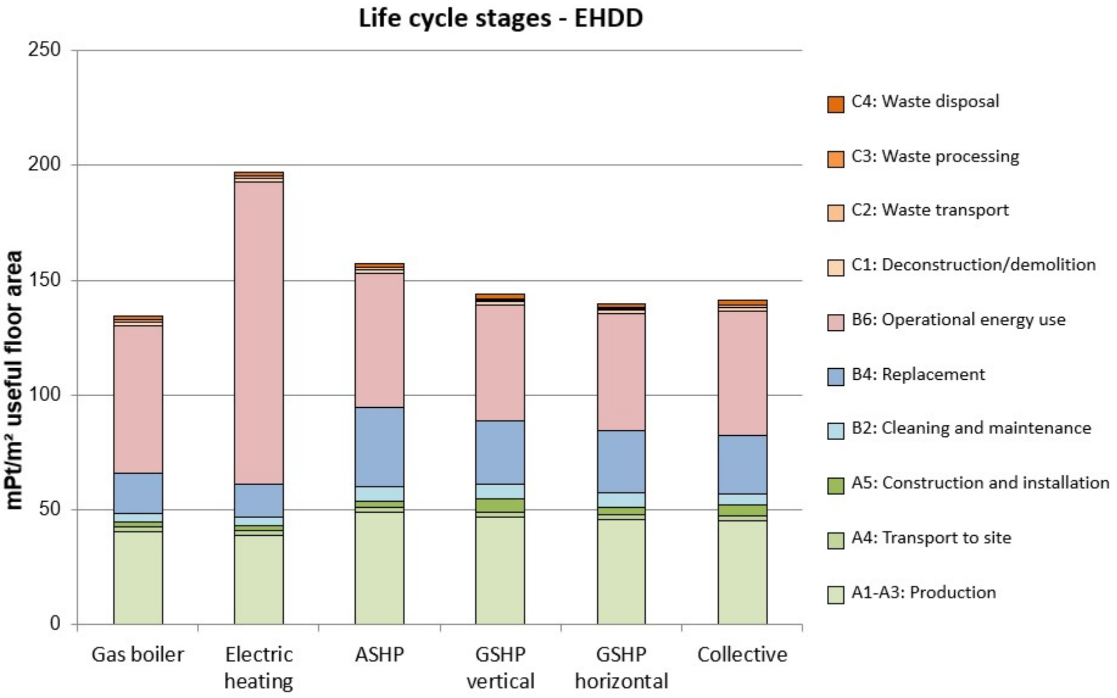


FIGURE 4.7: Life cycle stages (EHDD)

this indicator, would lead to a considerable underestimation of the true environmental consequences, as illustrated in Figure 4.8. The biggest impact is concentrated in only a few indicators: Climate change, depletion of fossil fuels, depletion of minerals and metals, PME and ecotoxicity. The difference between the gas boiler scenario and HP scenario's is attributed to the depletion of minerals and metals, which is mainly related to the material use in the heat pump themselves. If only the climate change is used as metric for the environmental impact, the scenario with a gas boiler would be the wost-in-class. The higher impact of climate change from the gas boiler, is caused by the usage of natural gas as energy source. For electricity use, the impact of climate change is smaller, but the impact on depletion of fossil fuels is much higher. It becomes clear that a more renewable energy mix, utilizing less fossil fuels and causing less climate change could end up reducing the impact of the electricity. This might result in electrical heating and heat pumps having a lower environmental impact than the gas boiler. This will be examined further in section 5.3

Technical Installations

In the figures 4.9 and 4.10 below, the environmental indicators for the gas boiler and GSHP with vertical bore field are depicted. Note that the environmental impact of the entire unit is given and thus not divided by the UFA ($50m^2$) as was done previously. Concerning the installation of the gas boiler, the environmental impact is well distributed over all components and indicators. The emission and control part has the highest impact, which can be linked to the large impact of the radiators, as was discussed above with the GSHP (figure 4.4). The most significant impacts stem from climate change, ecotoxicity and depletion of abiotic resources - minerals and metals, and fossil fuels. Conversely, for the heat pump, the unit itself is responsible for the biggest impact, primarily driven by 'climate

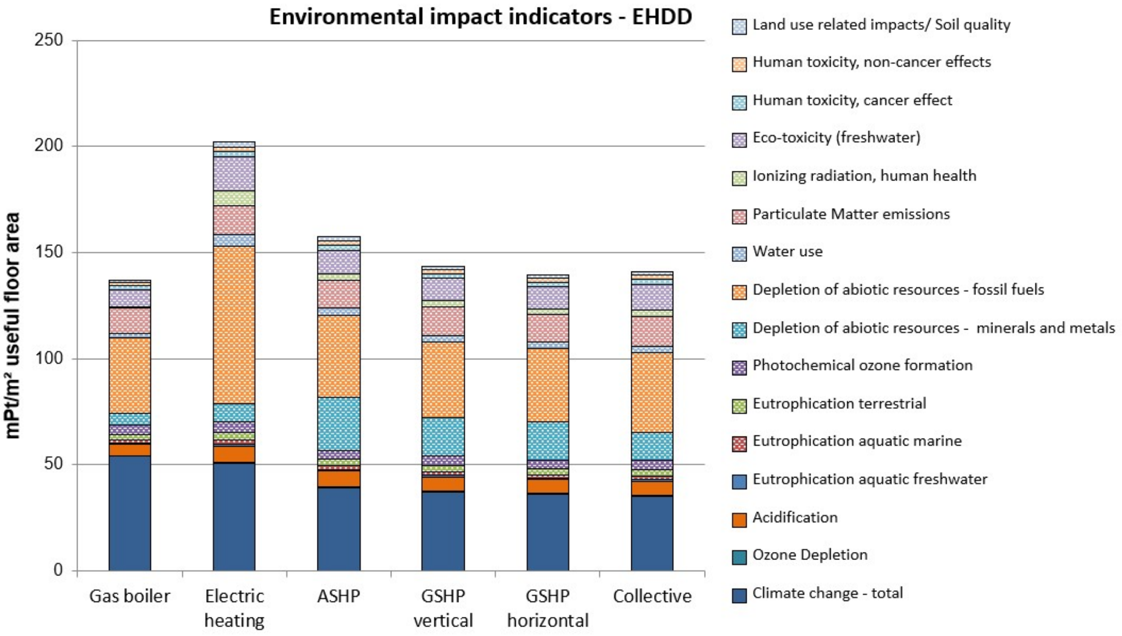


FIGURE 4.8: Environmental impact indicators (EHDD)

change' and 'depletion of abiotic resources - minerals and metals'. Also, the big difference in environmental impact between the gas boiler and the heat pump is demonstrated again.

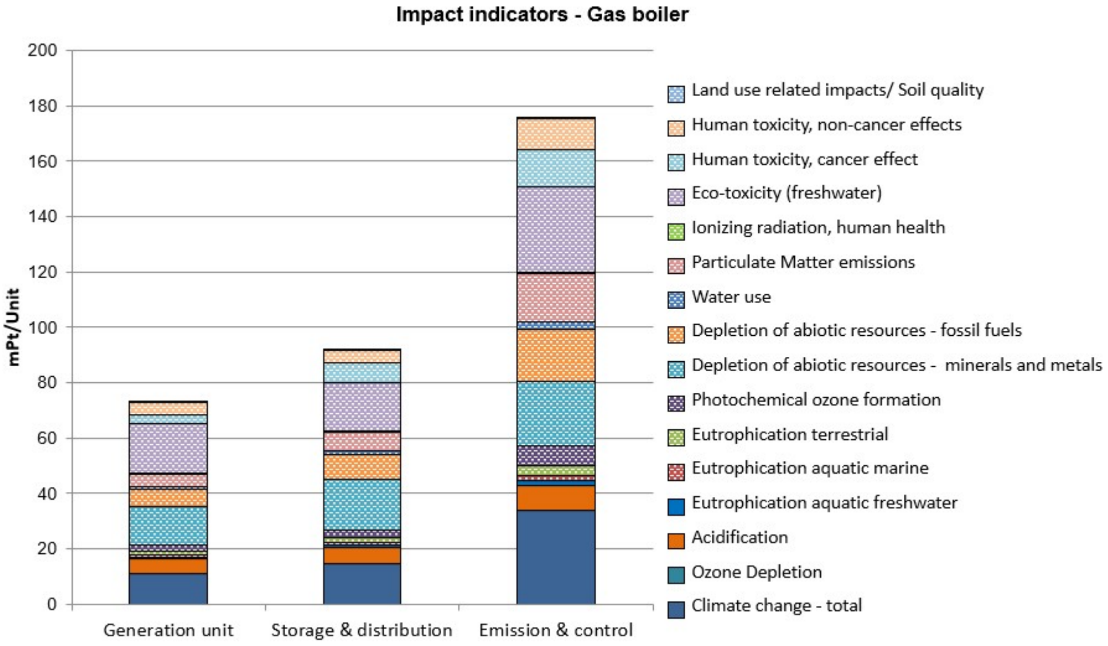


FIGURE 4.9: Impact indicators gas boiler

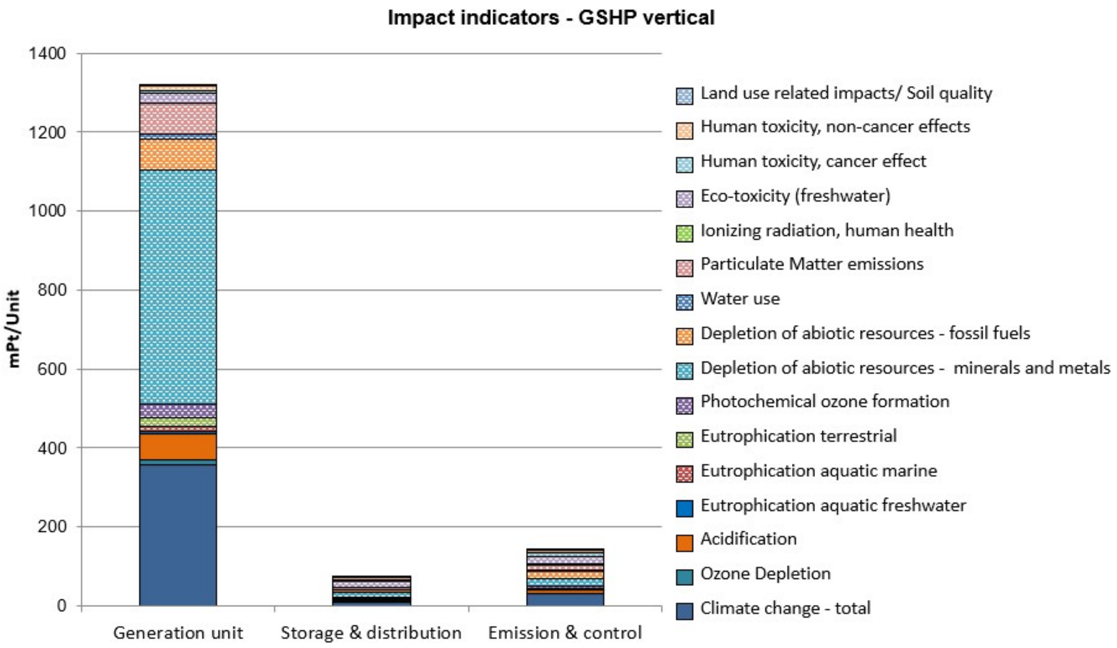


FIGURE 4.10: Impact indicators GSHP

4.2 Assessment Heating Systems - RBC method

The evaluations have been repeated, this time utilizing a dynamic calculation method based on RBC, for estimating operational energy use. For the buildings and the technical installations, the same models are applied. Both the impact of the materials and energy use as well as the impact of the different environmental impact indicators have been depicted below. The resulting impact of different life cycle stages has not been displayed this time, as the outcomes are similar to the previous assessment, except for the operational energy use, which has already been accounted for in the materials and energy use analysis. The energy use in the different scenarios was based on a simulation of the collective scenario, which means it is not an accurate representation for the energy use of the individual scenarios. The collective scenario will have a different control strategy than an individual gas boiler or heat pump, taking into account the thermal inertia. The gas boiler has a low thermal inertia and a higher heating power, such that the demand can be met in short notice. This would result in slightly lower heat losses in the gas boiler and electric heating scenarios, which is not accounted for when using a single simulation. For the collective scenario this effect will be even bigger, due to an even higher thermal inertia. The losses of the distribution network and storage tanks are subtracted for the individual scenarios. One advantage of the collective system that is not taken into account, is that due to non-simultaneous heat demand of the different buildings, the peaks in heating demand will be lower and more spread out. Because of this, the GSHP could operate at a higher COP, reducing the energy use. This might compensate the heat losses in the distribution network. Further, the simulation data did not allow to calculate the energy for DHW and CH separately. The impact of both energy demands is summed up, in figure 4.11 represented by the impact of energy use for heating.

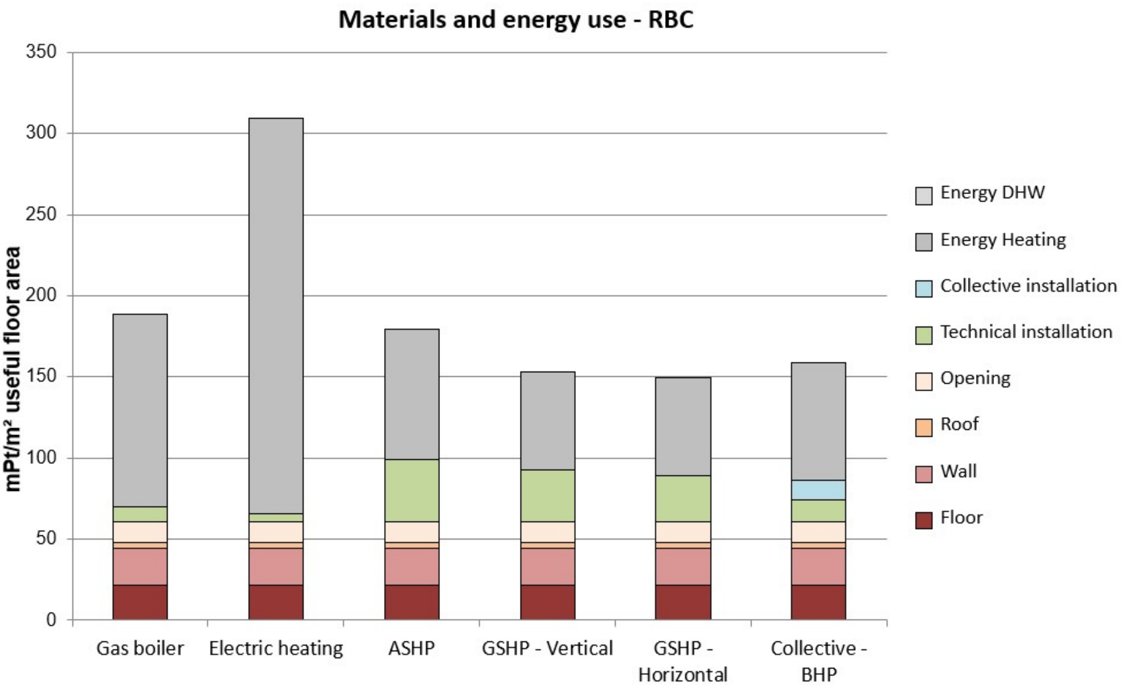


Figure 4.11: Materials and energy use (RBC)

The energy use estimated through RBC appears to be significantly higher than the previous

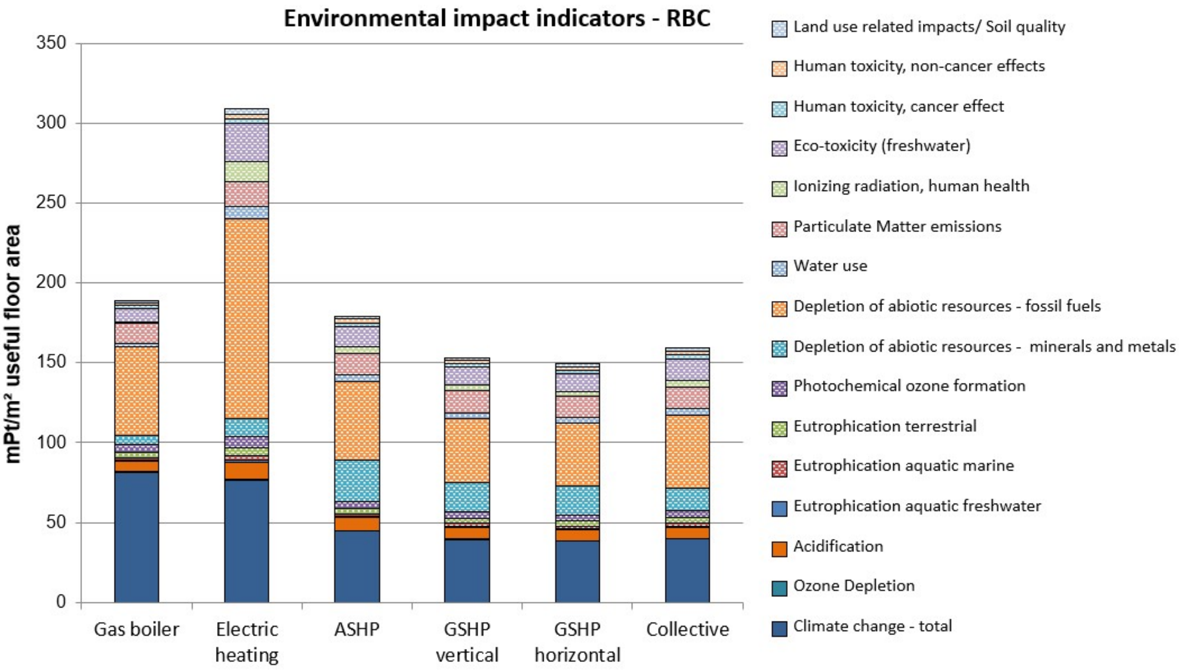


FIGURE 4.12: Environmental impact indicators (RBC)

EHDD-based estimations. This increase in energy use makes the scenario with a gas boiler (189 mPt/m^2) have a higher environmental impact than the heat pump scenarios. The GSHP with a horizontal bore field ends up having the lowest impact of 150 mPt/m^2, closely followed by the variant with a vertical bore field (154mPt/m^2). The scenario with an ASHP lies closer the gas boiler with 179 mPt/m^2. The electric boiler (309 mPt/m^2) is by far the worst. The collective system (164mPt/m^2) still fares better than the boiler and the ASHP but has a higher impact than both scenarios with a GSHP. Interestingly, the energy use for all scenarios with a heat pump do not deviate to much from the estimation with the EHDD method. This shows again that the estimation is based on a scenario with a heat pump and that the energy use of the gas boiler and electric heating is overestimated. The significant difference in energy use between the collective scenario and individual scenarios with a GSHP is again caused by the distribution losses. A small improvement in the insulation level of the distribution network would decrease this heat loss. If the reduction in impact caused by heat loss is less than the increase in impact caused by material use, the collective system might ultimately outperform the individual scenarios with a GSHP.

The distribution of environmental impact indicators, depicted in figure 4.12, is again dominated by climate change and the depletion of fossil fuels, and further emphasizes the importance of both indicators. It underscores the primary pathway to reduce the environmental impact of these scenarios, by focusing efforts on mitigating climate change and managing the sustainable use of abiotic resources. The main origin of both indicators is energy use, mainly the operational phase but also in other stages.

4.3 Conclusion

In this chapter, the environmental impact of the different scenarios was determined. The analysis of this environmental impact was conducted based on several perspectives. First, the impact of material use of the different system components and operational energy use was analyzed. A comparison between the technical installations revealed that the boilers appeared to have only a minor impact compared to the heat pumps in terms of material use. the heat pump installation even exhibited the highest impact among all system elements. When comparing the analysis of the small dwellings from 'De Schipjes' to a reference model from Totem, it was observed that the larger buildings ended up having a lower impact per UFA. This reduction was the largest for the technical installation, making the energy use even more prominent. With its high production efficiency, the reference scenario with a heat pump benefits even more than for the use case, resulting in a lower impact than the reference scenario with a gas boiler.

In terms of energy use, the heat pumps exhibited a lower impact due to their higher production efficiency. However, because the current electricity mix has a higher environmental impact per MJ compared to natural gas, this effect was partly negated. This led to electric heating being the scenario with the highest overall impact, despite the lower energy use. Depending on the energy calculation method, either the scenario with a gas boiler or GSHP came out on top. The gas boiler came out worse for with the calculation based on the RBC method, because the higher heating rate and lower heating losses were not accounted for in the single simulation. The core idea of distributing the impact of a collective system across its users led to a lower impact regarding material use. However, this reduction was cancelled due a higher impact of its energy use, caused by distribution losses. The collective scenario ended up being competitive with the individual GSHP scenarios in terms of total environmental impact. This certainly shows the potential of the collective scenario, keeping in mind the improvements that still can be made and certain advantages and disadvantages for the other scenarios that were not taken into account. This also provides a clear incentive for further research aimed at optimizing such systems even further.

Secondly, the impact of the different environmental impact indicators was analyzed, dominated by climate change and the depletion of fossil fuels. Their impact mainly originated from the high fossil fuel intensity of the used energy sources, i.e. natural gas and electricity, in turn also leading to climate change due to greenhouse gas emissions. However, solely considering the climate change, certainly leads to a severe underestimation of the actual environmental impact.

The impact of the different life cycle stages was examined as well. The environmental impact was found to be concentrated in the product stage (A1-A3), the replacement module (B4) and the operational energy use module (B6). The operational energy use seemed to have a substantial impact, depending on the applied calculation method. The implementation of the RBC-based method resulted in different and overall higher energy use, leading to different conclusions compared to the EHDD method. Electric heating had in both cases the highest impact.

Chapter 5

Sensitivity Analysis

Several assumptions and choices have been made during the modelling of the different scenarios. In this chapter, the effect of some assumptions will be investigated further. First, the generic heat pump model from Simapro will be compared to the different heat pump models from the PEP datasheets. Next to the different heat pump models, also different refrigerants will be considered. Finally, the effect of the electricity mix will be investigated.

5.1 Heat Pump Models

Because the technical installation of heat pumps seemed to have a substantial impact, the effect of using different LCA data will be investigated. Different heat pump models will be compared to each other and to the generic model, based on their PEP datasheets. Each heat pump will be modelled with a leakage factor of 2% per year, to focus mainly on the material use. The impact of the different refrigerants will be discussed in the next section. The comparison contains for each type of heat pump (GSHP, ASHP, collective HP) one generic component from Totem, based on data from Simapro and one or more based on LCA data from available datasheets of distinct manufacturers. Because of the limited availability of LCA data and lacking information from these datasheets, some additional heat pumps were modelled based on the LCA data from Simapro. In table 5.1, an overview is given of the different heat pump models, with their mass, nominal heating power and manufacturer. If the LCA data from Simapro was used, it is indicated as well. The components in bold are the ones used in the analysis from the previous section.

For the individual scenarios featuring a GSHP, only one PEP-datasheet could be obtained from *Daikin*. However, this specific model also included a storage tank. Regrettably, due to insufficient information regarding the decomposition of both the heat pump and storage tank, this data was initially deemed unsuitable for analysis. For reference, a non-PEP datasheet was obtained for a GSHP from *Vaillant* with a nominal heating power of 5.65 kW. Because this datasheet did not contain any LCA data, the component was modelled similar to the generic model from Totem, through a mass-based extrapolation from the model in Simapro. Now the impact of the GSHP from *Daikin*, *Vaillant* and the reference model from Totem can be compared in figure 5.1. For the ASHPs, next to the generic model from Totem, two PEP datasheets were retrieved from different manufacturers, *Ariston* and *Viessmann*. Additionally, a component was modelled based on a datasheet from *Vaillant*, to compare the GSHP and ASHP with similar heating power, from the same manufacturer. When comparing both components, the ASHP seems to be 10kg heavier than the GSHP.

This confirms the statement from the previous section. However, the difference in mass is only small compared to the 75kg difference between the two models used in Totem. For the collective scenario, no generic component is available in Totem. Therefore a generic component was created, based on a datasheet from *Viessmann* and again modelled through a mass-extrapolation of the generic data from Simapro. Two other GSHPs were modelled, based on LCA data from a PEP datasheet from *Daikin* and *Solaronics*.

The data in Table 5.1 clearly shows that the mass of heat pumps can vary significantly between different manufacturers. Because the Components in Simapro are modelled based on their mass, this can result in big differences in impact. Additionally, it is important to note that there is no linear relationship between the mass of the unit and its nominal power. In Simapro, this linear relationship is used to model a GSHP for collective heating systems of 30 kW by combining three 10 kW heat pumps. However, the gathered data in the table does not support this assumption. Therefore, this approach was not taken in this study. Instead, a mass-based extrapolation was used to model the collective GSHP, as mentioned previously. This mass-based extrapolation is valid if the materials of the heat pump scale linearly with the weight. It was demonstrated that this is more or less the case, even across different manufacturers. A detailed overview of the material decompositions of the different HPs is retrieved from the PEP datasheets, which can be found in appendix A.

Apart from the mass and material decomposition, a different type and amount of refrigerant is employed in each heat pump. It was found that the amount of refrigerant scales with the mass of the heat pump in most cases. Only the HP from *Solaronics* shows a large deviation, utilizing only a very small amount of refrigerant. As mentioned before, the effect of the different refrigerant types will be discussed further in the next section.

Manufacturer	**Type**	**Nominal power**	**Mass HP**	**Refrigerant amount**	**Refrigerant type**
Totem (Simapro)	**GSHP**	**9 kW**	**129 kg**	**3.09kg**	**R134a**
Vaillant (Simapro)	GSHP	7 kW	160 kg	2kg	R410a
Daikin	GSHP	5.6 kW	241 kg	1.7kg	R32
Totem (Simapro)	**ASHP**	**9.7 kW**	**205 kg**	**3.09kg**	**R134a**
Ariston	ASHP	5.65 kW	87.5 kg	1kg	R32
Vaillant (Simapro)	ASHP	7 kW	150 kg	0.9kg	R290
Viessmann	ASHP	8 kW	132 kg	1.68kg	R32
***Viessmann* (Simapro)**	**GSHP**	**42 kW**	**298 kg**	**7.7kg**	**R410a**
Daikin	GSHP	33.5 kW	228 kg	9kg	R32
Solaronics	GSHP	40 kW	351 kg	1.96kg	R410a

TABLE 5.1: Heat pump models - characteristics and source

The distribution of the environmental impact based on the indicators of each model is shown in figure 5.1. The selected models for the analysis in previous section are enclosed by a dashed line. The heat pump models selected for the use case analysis seem to have the lowest impact for the individual and collective scenario with a GSHP. For the scenario with an ASHP, the impact of the selected model lies between the other two options. Normally, these generic components should be worst in class, as they are based on worst-case scenarios, which is apparently not the case. The distribution of the different indicators is similar across most heat pumps. However, the two results from *Daikin* stand out. In the components based on PEP datasheets from *Daikin*, the light blue and orange sections represent the impact on human toxicity, specifically cancer and non-cancer effects, respectively. These impacts are not observed to be significant in the other models. Due to the lack of information about how the LCA was performed or how the LCA data was obtained, no further elaboration on the origin of these impacts was made. One conclusion that can be drawn from this analysis is that there is a significant disparity between the impacts of different heat pumps from various manufacturers. For most heat pumps, the main sources of impact are climate change and primarily the depletion of minerals and metals. This either indicates the necessity for a more standardized LCA methodology or suggests that some heat pump manufacturers are focussing more on the environmental impact of their products than others.

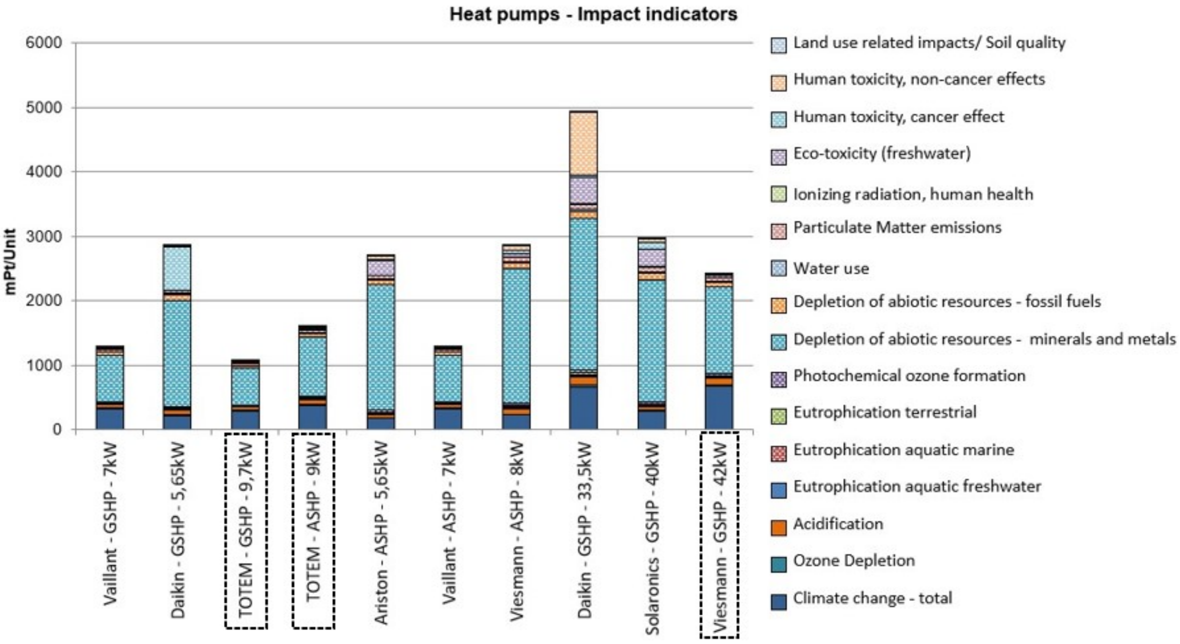


Figure 5.1: Comparison heat pumps based on impact indicators

To investigate the effect of the model choice, the analysis from the previous chapter was repeated using the heat pumps with the highest environmental impact. For the individual scenarios, the GSHP from *Daikin* and the ASHP from *Ariston* were selected, both with a nominal heating power of 5.65 kW. In the Collective scenario, also the GSHP from *Daikin* was chosen, with a heating power of 33.5 kW. Because a storage tank is already included in the data of the GSHP from *Daikin*, it was left out of the technical installation for this model. The analysis was performed both with the EHDD and the RBC method, giving different results, shown in figures 5.2 and 5.3. After implementing the HPs with a higher environmental impact, the results have completely shifted in favor of the collective system, comparing all heat pump scenarios. Since the environmental impact of the collective heat pump is distributed among all consumers, its effect is much smaller. For the individual scenarios, the resulting impact of the GSHPs lies close to that of the gas boiler when using the RBC method, while the ASHP still exhibits a higher impact. Under the EHDD method, all heat pump scenarios perform far worse than the gas boiler. These results underscore the importance of the applied calculation method and, more importantly, the LCA data used in the study and the assumptions made regarding the mass of the heat pumps.

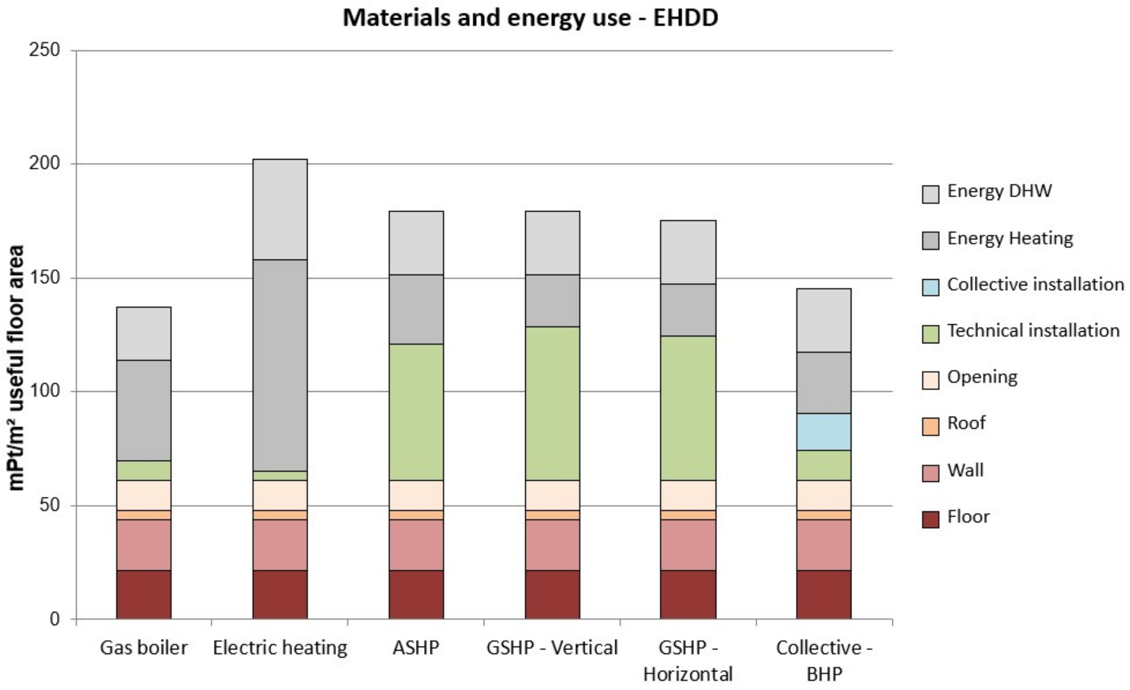


FIGURE 5.2: New analysis - HPs with highest impact - EHDD method

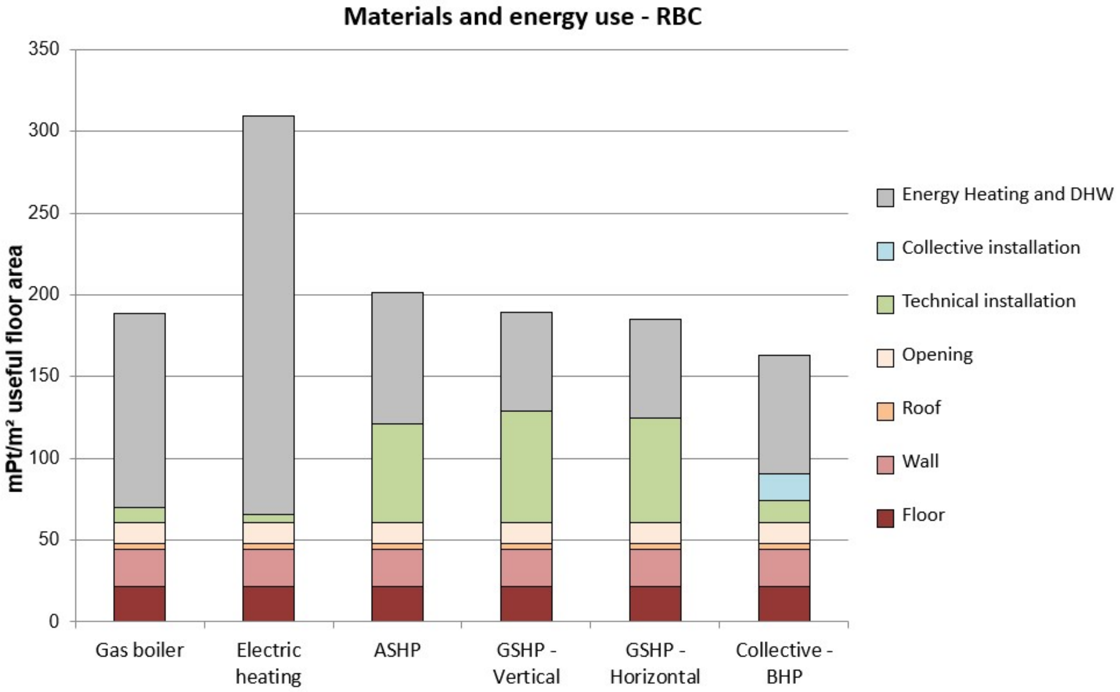


FIGURE 5.3: New analysis - HPs with highest impact - RBC method

5.2 Refrigerants

In the literature was found, that refrigerants have a big environmental impact, which might affect the total environmental impact of HPs. To verify this, the environmental impact of a heat pump with refrigerant was compared to one without refrigerant. For this analysis, the generic data from Simapro was used. For the HP model without refrigerant, the 3.09kg R134a was removed. According to figure 5.4, the refrigerant indeed seems to have a substantial impact on the total impact of the heat pump, more specifically on climate change. For this reason, refrigerants with a high environmental impact are being phased out. Currently, R134a and R410a are being used a lot, but in the future, refrigerants with a Global Warming Potential (GWP) of more than 750, such as R134a and R410a will be forbidden. For this purpose, the employment of natural refrigerants such as propane (R290), CO_2 (R744), butane (R600) or ammonia (R717), with a much lower GWP between 0 and 4 is currently being investigated.

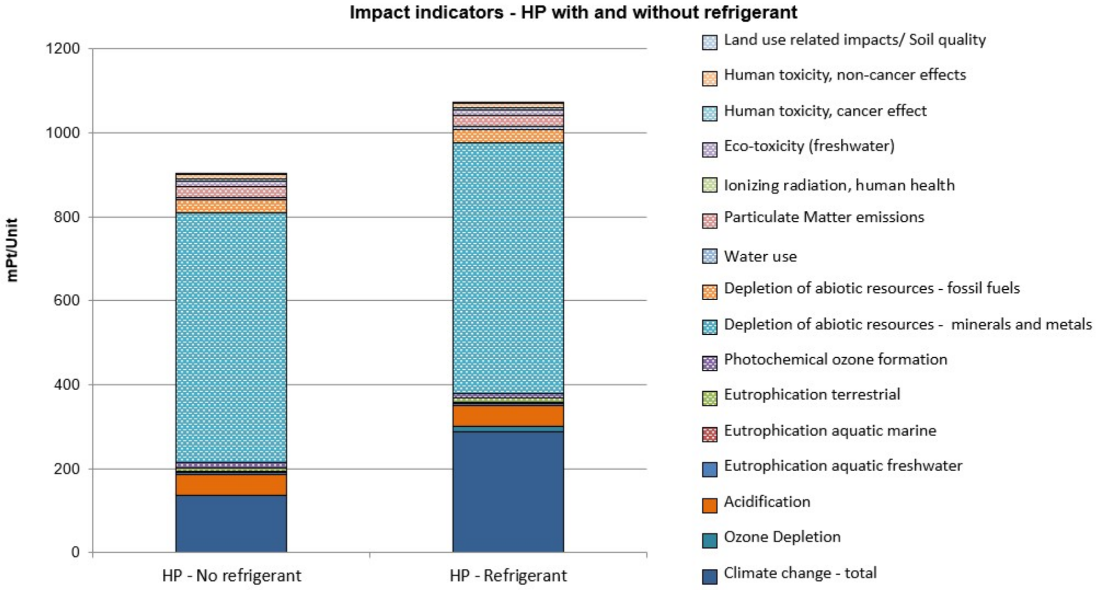


FIGURE 5.4: Comparison environmental impact of HP with and without refrigerant

5.2.1 Refrigerant Types and Characteristics

Because Simapro only provided information about R134a, another database was consulted for this analysis. The German database *Ökobaudat*, provided information about other refrigerants as well. However, only LCA data on a part of the environmental impact indicators was available. Here, the environmental impact of R134a, R410a, R32, R290 (propane) and R744 (CO_2) will be investigated. The results are illustrated in Figure 5.5. The available impact indicators are shown in the legend. Figure 5.6 provides a more detailed examination of the impact indicators for propane and CO_2. Of all refrigerants, R410a appears to have the largest environmental impact, followed by R134a and R32, primarily caused by their impact on climate change. Propane and CO_2 exhibit a much lower impact, from which the difference is attributed to the effect of propane on ozone layer depletion. Overall, CO_2 has the lowest environmental impact, making it a promising option as a refrigerant.

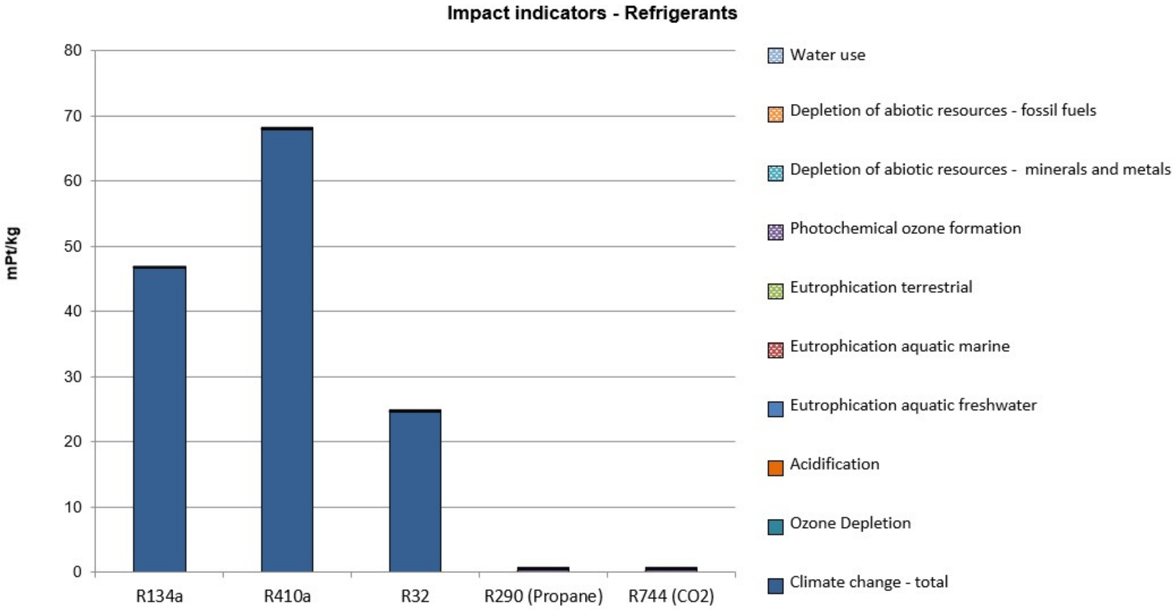


Figure 5.5: Environmental impact of refrigerants

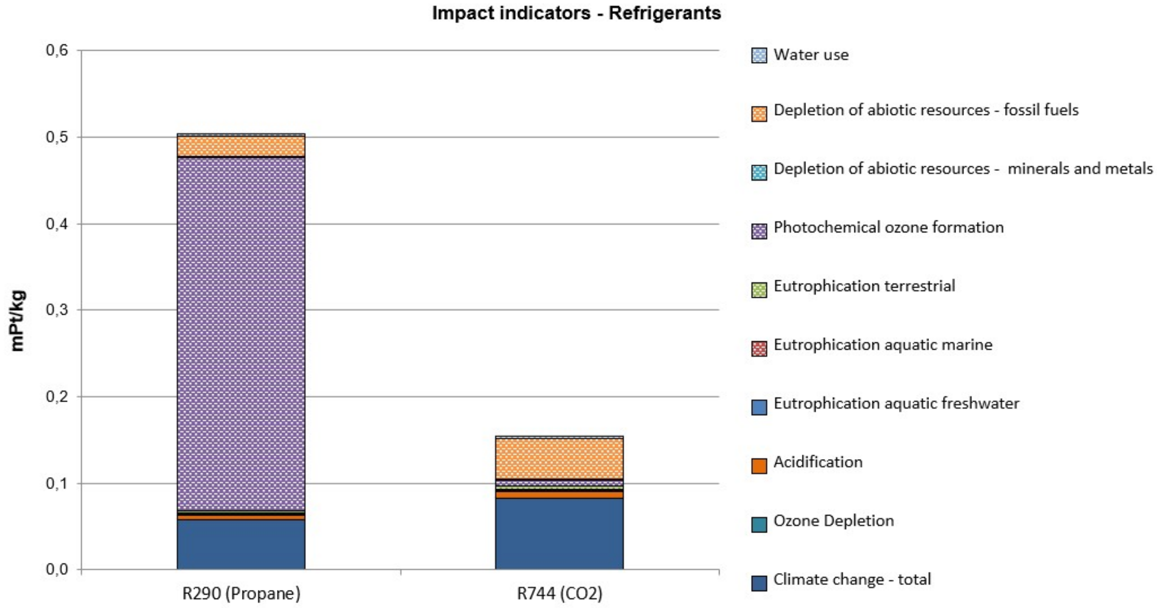
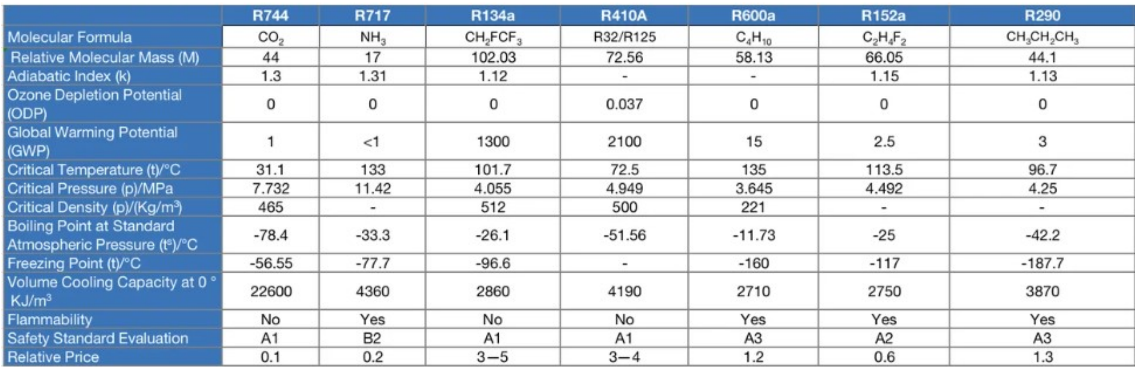


Figure 5.6: Environmental impact of propane and CO_2

Apart from environmental impact, other criteria are important to assess the potential of refrigerants. Thermodynamic, physical, chemical and economic characteristics have to be considered as well. Table 5.7 provides an overview of some key characteristics of the refrigerants investigated above, retrieved from the International Society of Automation Interchange [6]. Some important characteristics are the adiabatic index k, critical temperature and pressure, temperature range, viscosity, flammability, toxicity, cost, etc. The cost indicated in the table is determined relative to R12. The adiabatic index k, is the ratio between the thermal capacity at constant pressure and constant volume (c_p/c_v). This value should be as low as possible, to minimize the required compression power [77]. The critical temperature should be high and the temperature range, such that the the heat transfer can easily take place in the two-phase region. Further, the critical pressure should be low enough, to limit the requirements on the thickness of the pipes and compressor. A good thermal conductivity and thermal capacity ensure a good heat transfer. The volume cooling capacity (q/v) in the table represents the amount of heat that can be extracted or stored per volume of refrigerant. A higher capacity implies a smaller device and less refrigerant. By choosing a refrigerant with a high volumetric cooling capacity, the same cooling can be achieved with a lower amount of refrigerant, thereby reducing the environmental impact of the installation. Regarding chemical properties, refrigerants should have low flammability and be non-toxic to minimize safety risks. Finally, the cost of the refrigerant is an important factor to consider as well.



	R744	R717	R134a	R410A	R600a	R152a	R290
Molecular Formula	CO_2	NH_3	CH_2FCF_3	R32/R125	C_4H_{10}	$C_2H_4F_2$	$CH_3CH_2CH_3$
Relative Molecular Mass (M)	44	17	102.03	72.56	58.13	66.05	44.1
Adiabatic Index (k)	1.3	1.31	1.12	-	-	1.15	1.13
Ozone Depletion Potential (ODP)	0	0	0	0.037	0	0	0
Global Warming Potential (GWP)	1	<1	1300	2100	15	2.5	3
Critical Temperature (t)/°C	31.1	133	101.7	72.5	135	113.5	96.7
Critical Pressure (p)/MPa	7.732	11.42	4.055	4.949	3.645	4.492	4.25
Critical Density (p)/(Kg/m^3)	465	-	512	500	221	-	-
Boiling Point at Standard Atmospheric Pressure (t^s)/°C	-78.4	-33.3	-26.1	-51.56	-11.73	-25	-42.2
Freezing Point (t)/°C	-56.55	-77.7	-96.6	-	-160	-117	-187.7
Volume Cooling Capacity at 0 ° KJ/m^3	22600	4360	2860	4190	2710	2750	3870
Flammability	No	Yes	No	No	Yes	Yes	Yes
Safety Standard Evaluation	A1	B2	A1	A1	A3	A2	A3
Relative Price	0.1	0.2	3—5	3—4	1.2	0.6	1.3

FIGURE 5.7: Refrigerant Properties (copied from [6])

R410a seems to have the highest environmental impact per kg. However, because of its higher cooling capacity, a lower amount of refrigerant is required than R134a. The characteristics of R32 are not shown in the table, but with 4812kJ/m^3, it has an even higher cooling capacity than R410a. Its other characteristics are similar to R410a [78]. Because of its lower environmental impact and good thermophysical properties, R32 is often selected as a refrigerant. Propane and carbon dioxide rank as the refrigerants with the lowest environmental impact. However, despite propane's excellent thermophysical properties, it is highly flammable and more expensive than CO_2. Conversely, CO_2 is non-flammable but has a higher critical pressure, increasing the requirements for compressors and pipelines and thereby increasing the cost of the installation. Additionally, its adiabatic index is higher, necessitating more compression power. But considering its other, favorable thermophysical properties and low cost, CO_2 demonstrates significant potential as a refrigerant. Moreover, CO_2 has the highest volumetric cooling capacity, meaning a smaller amount of refrigerant is needed [6].

During the comparison of different heat pump models, substantial differences in the amount of refrigerant needed were observed. This variation can be attributed to the design and nominal heating power of the heat pump, as well as the type of refrigerant used and its properties. Heat pumps employing R134a generally required more refrigerant than those using R410a or R32. This observation can be linked to the volumetric cooling capacity of the refrigerants. For CO_2, the volumetric cooling capacity is even higher, meaning even less refrigerant is required.

5.2.2 Effect of the Employed Refrigerant Type

With this background, the analysis between the different scenarios can be conducted again, but with different refrigerants. In figure 5.8 the generic GSHP model from Totem is modelled with both R134a and CO_2 as refrigerant. Due to the lack of detailed information on how the amount of refrigerant is determined, both heat pumps were modeled with 3.09 kg refrigerant, implementing the data from the German database *Ökobaudat*. Note that different LCA data is used regarding the refrigerants, resulting in different impacts of the HP compared to previous analyses. It is clear that R134a significantly contributes to the total environmental impact of the heat pump, whereas the addition of CO_2 has a negligible effect. In reality, the amount of employed CO_2 will be lower, due to its superior volumetric cooling capacity. Nonetheless, this reduction will have an insignificant impact, as the overall environmental contribution of the refrigerant remains minimal.

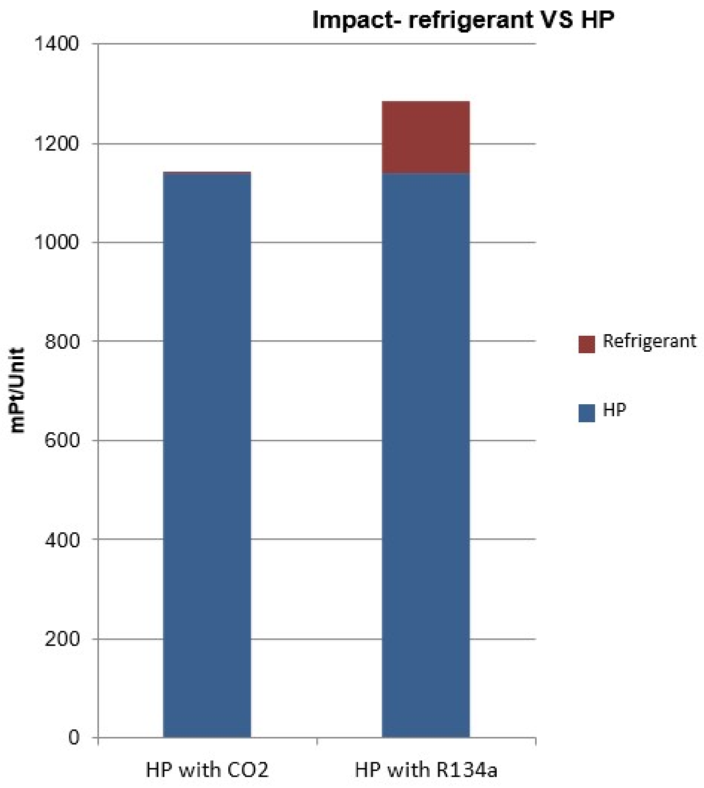


FIGURE 5.8: Comparison HP with R134a and CO_2

Because only part of the impact indicators are provided, a comprehensive analysis of the different refrigerants, as was done for the heat pump types, could not be made. With some reasoning, the possible effect of the different refrigerant on the analysis can be determined. Due to the lower impact of the technical installation, the impact of the different heat pump scenarios would be lower than before, maybe even surpassing the gas boiler for both energy calculation methods. However, the effect would be smaller for the collective scenario, as the impact is distributed over all users. The collective scenario could end up with a higher impact than the individual scenarios with a GSHP and vertical bore field, because of the lower impact of the technical installation. A comparative analysis between the individual and collective scenario with GSHP and vertical bore field was conducted. For the estimation of the energy use, the RBC-based method was applied. The results are as predicted, with a higher impact for the collective scenario, as is shown in figure 5.9. Note that in the first analysis with the RBC-based method, the collective scenario performed better than the individual scenario with a vertical bore field. However, here different LCA data is used for the refrigerants, retrieved from the *Ökobaudat* database. This again underscores the sensitivity of the assessments to the selected data. However, the gap between both scenarios has decreased. Note that the reduction in environmental impact of 2.5 mPt of the collective scenario is smaller than the 6 mPt reduction of the individual scenario when changing the refrigerant type. This confirms the supposition that the effect is higher for the individual scenarios.

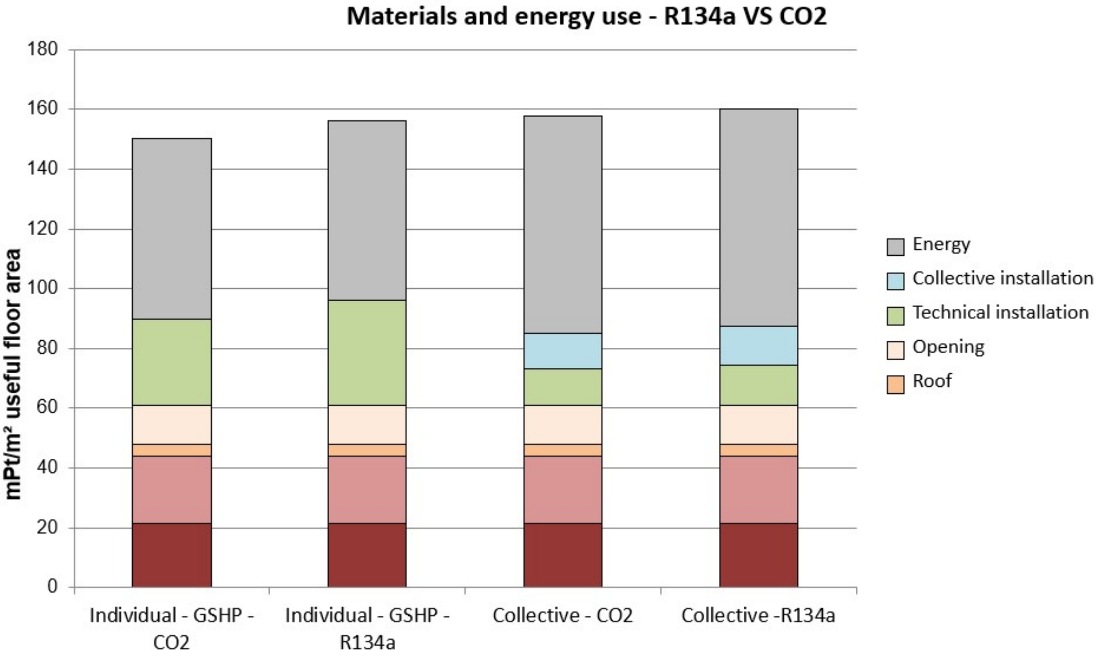


FIGURE 5.9: Collective and individual scenario with R134a and CO_2

5.3 Electricity Mix

The energy use varies depending on the selected calculation method. However, for both the EHDD and RBC methods, it accounts for a significant portion of the environmental impact, especially for scenarios involving a gas boiler or electric heating. Utilizing a different calculation method or changing the electricity mix could significantly affect the overall environmental impact and thereby change the ranking. First, the effect of the electricity mix will be investigated. Secondly, the currently implemented static energy mix will be compared to a dynamic energy mix. For these analyses, the results of the RBC simulation will be used, providing an hourly electricity use of the collective system.

5.3.1 Static vs Dynamic Electricity Mix

In the previous analyses, a static electricity mix was considered. In reality, this mix is dynamic, continuously changing, and consequently varying its environmental impact. To get closer to reality, a dynamic electricity mix from 2021 is considered with a time interval of one hour. The electricity mix for this analysis was retrieved from the Entso-e, transparency platform [79]. The LCA data used for this analysis is retrieved from electricity maps, providing two sets of data for the Belgian electricity mix: the environmental impact caused solely by operational emissions and the impact assessed over the entire life cycle. The LCA data from this analysis is different from the LCA data from Simapro, meaning the results will differ from previous analyses. Therefore, in addition to the impact of the scenario with a dynamic mix, the scenario with a static mix is recalculated as well, based on the same data. For both scenarios, the environmental impact is represented in kg CO_2 equivalent per kWh. For each generation type, the emission factors of both scenarios are gathered in table 5.2, mostly coming from the IPCC (2014) Fifth Assessment Report. No further information was found regarding the considered environmental impact indicators or the applied conversion factors. A complete breakdown of the impact distribution across various impact indicators is therefore not possible. For the energy use, the results from the RBC-based method are implemented, giving the hourly electricity use of each scenario.

Generation type	**Life-cycle emission factor** $[gCO_2eq/kWh]$	**Operational emission factor** $[gCO_2eq/kWh]$
Biomass	230	0
Coal	820	760
Gas	490	370
Geothermal	38	0
Hydro	24	0
Nuclear	12	0
Oil	650	406
Solar	45	0
Wind	11	0

Table 5.2: Operational and Life-cycle emission factors from electricity maps [17]

In Figure 5.10, the environmental impact of the electricity mix, measured in kilograms of CO_2 equivalent, is depicted over time. This figure compares both the operational and life cycle assessment (LCA) impacts. The disparity between the impact of the operational phase only and the entire life cycle underscores again the underestimation of environmental impact when only the operational phase is considered. The lower values of environmental impact in certain periods can be attributed to the increased availability of wind and solar power.

In Figure 5.11, the energy use for the two scenarios is depicted. By multiplying the associated damages by the electricity use in each scenario, the dynamic impact of the electricity use for each scenario can be determined, as illustrated in Figure 5.12. If periods of high environmental impact coincide with periods of high energy demand, this will result in a higher overall impact, compared to the static electricity mix.

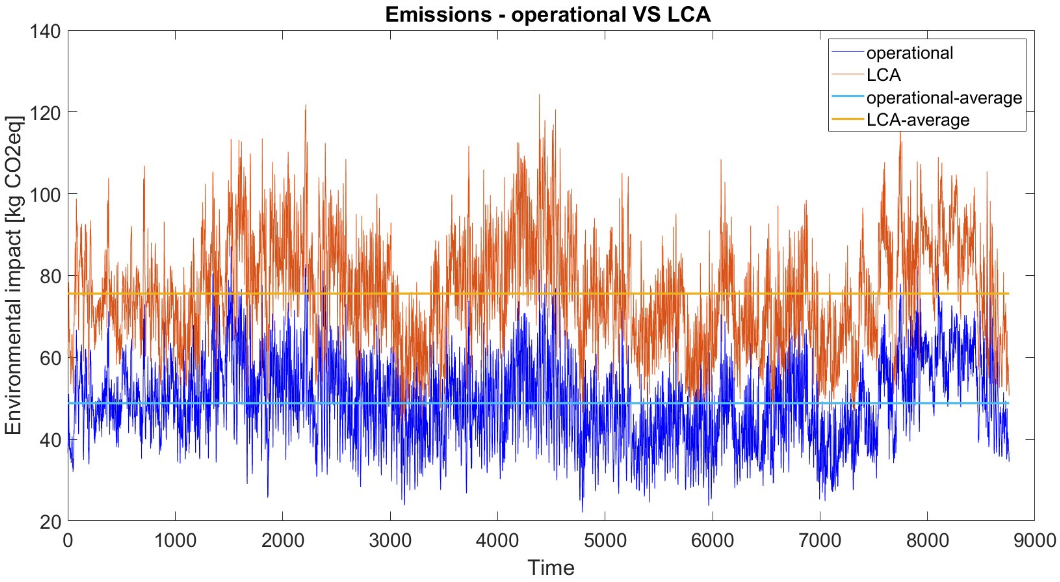


FIGURE 5.10: The environmental impact of the dynamic electricity mix in kg CO_2 equivalent

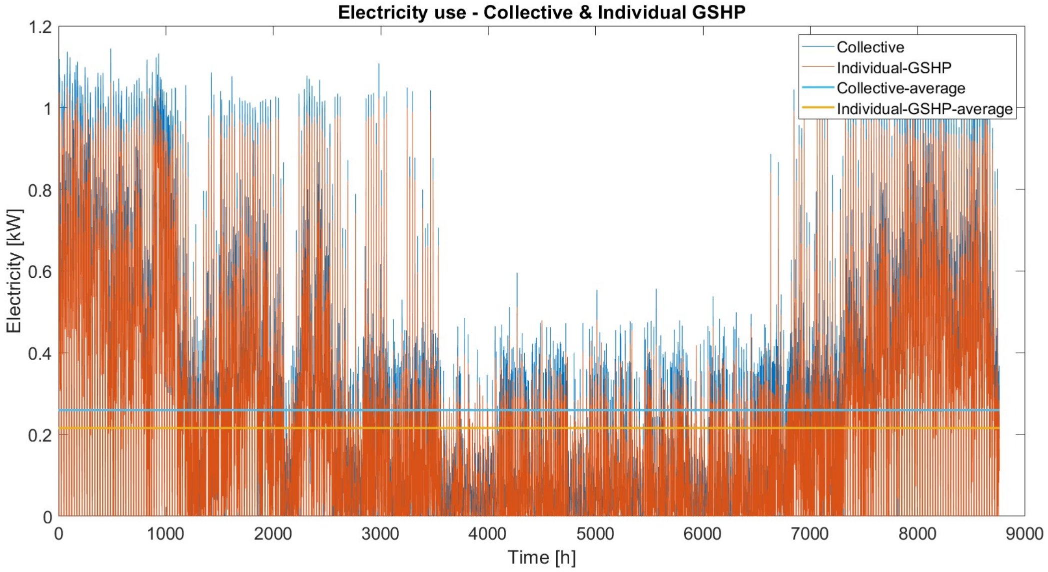


FIGURE 5.11: Electricity use of Collective and Individual scenario with GSHP

To assess the effect of using a static electricity mix instead of a dynamic mix, two scenarios

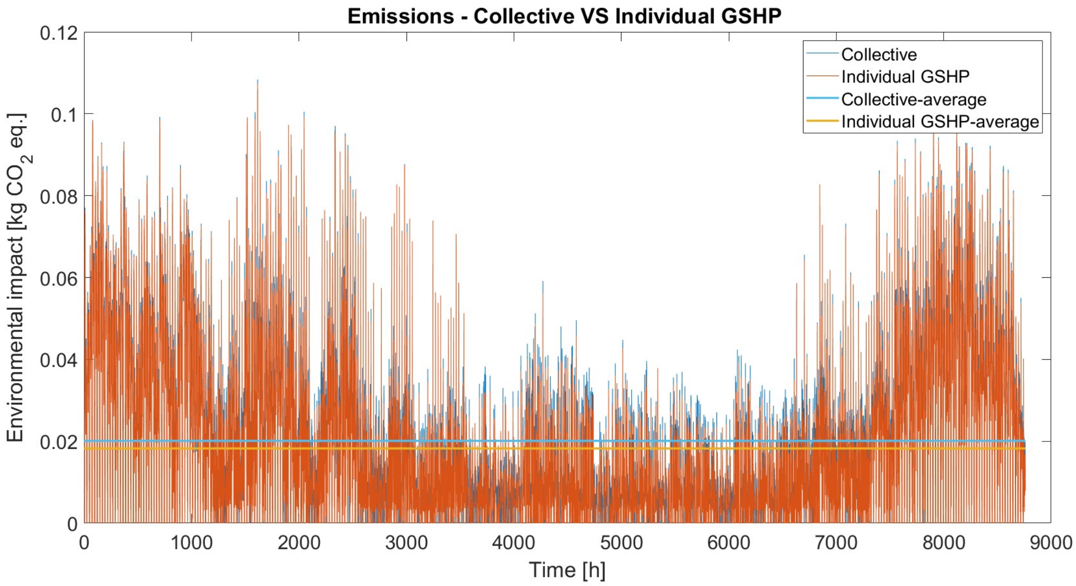


FIGURE 5.12: Emissions collective and individual GSHP

were compared: the collective scenario and an individual scenario with a GSHP. The impact of their energy use was evaluated for both a dynamic (blue) and static (red) electricity mix, depicted in figure 5.13. Additionally, for each of these four scenarios, the difference between the environmental impact considering only operational emissions or the entire life cycle was analyzed. Similar to the figure above, it is clear that considering only operational emissions results in a big underestimation of the actual impact. Furthermore, as determined in the previous section, the impact of the collective system is larger than that of the individual system due to distribution losses in the collective network. Apparently, the static electricity mix has a lower impact than a dynamic mix, attributed to the higher energy demand in emission-intensive periods. From another point of view: if the energy demand is higher during periods with low availability of wind and solar power, peak units will need to be activated, resulting in a higher emission intensity of the electricity mix. In all the previous analyses, a static mix was considered. Implementing a dynamic mix instead would lead to higher imp acts regarding energy use for the scenarios using electricity as an energy source. The scenario with a gas boiler would benefit from this. Because of the higher energy use of the collective system, the gap between the collective and individual scenario with HPs would again be increased.

5.3.2 Present vs Future Electricity Mix

The global energy use and its environmental impact can potentially be reduced through electrification, replacing fossil fuels with electricity. However, the current electricity mix exhibits a higher environmental impact than natural gas, see figure 4.2. To mitigate this, European countries plan to transition towards a more renewable electricity mix, increasing the share of wind, solar, hydro, biomass and other renewable sources. This transition does not necessarily imply a reduction in overall environmental impact, as the installation of new production capacity also has a substantial environmental footprint. While the impact of climate change might decrease, other impact indicators, such as land use and depletion of abiotic resources, could increase and must also be considered. A complete LCA of different electricity mixes could not be performed, as this would require an extensive analysis of the

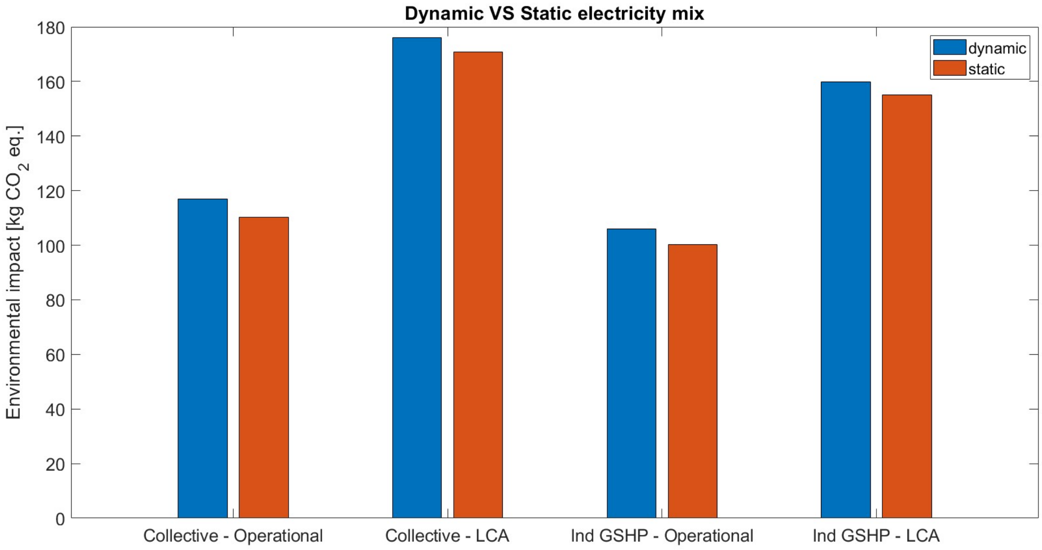


FIGURE 5.13: Comparison between dynamic and static electricity mix

different sources, changes in the electricity grid, its losses, etc. A simplified approach was taken to gain more insight into the environmental impact of possible future scenarios. A comparative analysis was conducted on the impact of the production of one GJ of electricity from various sources. Figure 5.14 illustrates the environmental impact indicators of several commonly used energy sources for electricity production. The LCA data was retrieved from Simapro, which in turn gets this from the Swiss database Ecoinvent, version 3.6. For each energy source, the impact at the high voltage level was taken, except for the rooftop PV, which is considered at the low voltage level. This implies that the environmental impact of the other sources is slightly underestimated, because the grid losses and grid use are not included. These losses and grid use should not be incorporated for the rooftop PV, except for a small injection into the grid.

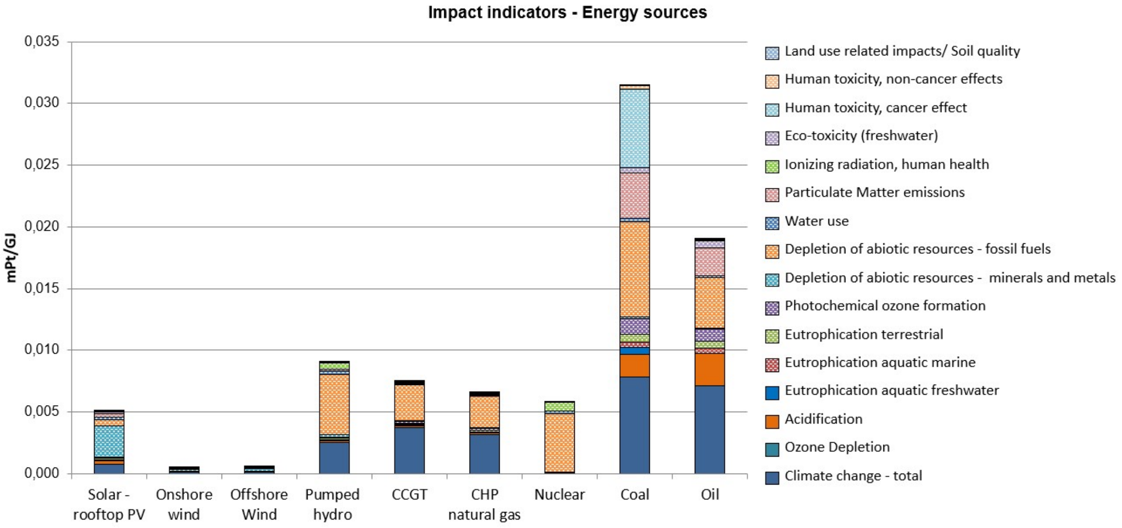


FIGURE 5.14: Environmental impact indicators of common energy sources

Coal and oil clearly exhibit the highest environmental impact. Therefore, the decision to phase out these energy sources as much as possible is a good one. Interestingly, pumped hydro storage has a higher impact than the combined cycle gas turbine. The higher impact of the hydro storage will probably be caused by the construction of the dam, requiring a lot of materials, energy use and land use. While nuclear performs better than both natural gas options, it still has a substantial environmental impact, mainly caused by the depletion of fossil fuels. A probable explanation for this high depletion of fossil fuels is the intensive production and construction processes of nuclear power plants. Notably, electricity generated by rooftop PV shows a relatively high impact compared to onshore and offshore wind energy, primarily due to the intensive use of minerals and metals during the production of the installation. Wind power seems to be the go-to option to minimize environmental damage caused by electricity generation. If only climate change would be considered, as is currently often the case, nuclear energy would have the lowest impact, together with wind power, followed by PV and then pumped hydro.

5.4 Conclusion

In this chapter, several assumptions were verified, and key elements with a high impact were further examined. The heat pump installations appeared to have a significant environmental impact and were investigated first. The substantial difference in environmental impact between the generic models from Simapro and the LCA data from different manufacturers highlighted the importance of the chosen LCA data and the corresponding heat pump model. If no LCA data is available, HPs are modelled through a mass-based extrapolation based on available LCA data. If this is the case, apart from the LCA data, the mass of the HPs is a determining factor for the impact of the component. The selection of different heat pump models resulted in a completely different hierarchy regarding the total environmental impact of the various scenarios. Against expectation, as they are developed considering worst-case scenarios, the models based on data from Simapro prevailed with the lowest impact. Apart from the heat pump model, also the effect of the selected type and amount of refrigerant was examined. A significant difference in environmental impact was observed among refrigerants, with CO_2 being the best option, closely followed by propane. However, properties other than environmental impact must also be considered when selecting refrigerants. Apart from a lower environmental impact, CO_2 has good thermophysical properties, apart from its high critical pressure.

Regarding the electricity mix, the static variant used in the analyses appears to slightly underestimate the actual environmental impact. This underestimation occurs because the dynamic electricity mix accounts for higher energy demand during periods when the electricity mix has a greater environmental impact, leading to an increased overall environmental impact. The environmental impact of electricity use currently exceeds that of natural gas by a considerable margin. However, if the current electricity mix is replaced with a more environmentally friendly mix that incorporates a higher share of renewable energy sources, this high impact can be significantly reduced. This change will particularly benefit heat pump scenarios, especially the collective scenario, because of the high distribution losses. Among the energy sources, wind energy had the lowest environmental impact, followed by PV panels, nuclear energy, and CCGT. Despite being a renewable energy source, pumped hydro surprisingly showed a substantial environmental impact, slightly higher than the CCGT.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

In summary, this thesis investigates the environmental impact of buildings, with the focus on their heating systems, through a comprehensive life cycle assessment (LCA). The methodology delineates the working principle of the applied MMG LCA method, which implemented in the MMG KU Leuven tool. Following this, the different scenarios were defined and modelled, estimating their energy use based on two methods. Five scenarios with an individual heating system can be distinguished and two with a collective heating system.

Chapter 4, holds a discussion of the results from the initial simulations. In the case where the EHDD calculation method is applied for the energy calculations, the scenario with a gas boiler outperforms all other scenarios, closely followed by the individual systems with a GSHP and the collective system. Despite the construction intensity of the bore fields, the ASHP exhibits a slightly higher impact than the GSHP scenarios, due to its the heavier heat pump model. On the other hand, applying the RBC-based calculation method, results in the gas boiler having a higher impact than all HP scenarios, including the collective scenario. It is important to note that the calculation based on the RBC method is based on the collective scenario and is therefore not entirely representative for the individual scenarios, least of all for the gas boiler and electric heating. This also shows in the higher impact of both scenarios, compared to the scenarios with a HP. The GSHP scenario with a horizontal bore field comes out on top with a slight advantage over the GSHP with a vertical bore field. This is because the construction of a horizontal bore field is less intensive. However, for both scenarios the same COP is assumed, whereas in reality, the vertical bore field operates at slightly higher COP. The collective system and ASHP closely followed both GSHP scenarios. The collective system could operate at an even higher COP than the vertical bore field, due to a smoother and more spread out heat demand. Electric heating exhibits by far the highest environmental impact for both calculation methods. Also for the collective scenario, replacing the BHP with an electric boiler for DHW results in a higher impact. For both energy calculation methods, the impact of energy use is very significant, particularly regarding the high impact of the electricity mix being about 2.5 times larger than natural gas. This high impact offsets part of the benefit of the high efficiency of the heat pumps. Regarding the environmental impact indicators, climate change and the depletion of fossil fuels have the biggest contribution to the total environmental impact. For the HP scenarios, the depletion of minerals and metals is substantial as well. Focusing solely on climate change leads to a severe underestimation of the actual environmental impact and can sometimes result in incorrect conclusions about which system or scenario has the lowest impact.

In chapter 5, the most important assumptions are verified and elements with the highest impact are examined in more detail. The impact of the HP installations is substantial, mainly coming from climate change and depletion of minerals and metals, and varies a lot between manufacturers. Implementing different models for the HP completely shifted the results in favour of the collective scenario. Similar to the comparison with the reference models, the impact of the material use of the collective scenario, is distributed over more users, making the impact of material use less and the energy use even more significant. Selecting more impactful heat pump models, is therefore in the benefit of the collective scenario. For the heat pump models, the employed refrigerant has an effect on the impact of the installation, and is mainly caused by climate change. Implementing natural refrigerants, such as propane or $CO2$, having almost no impact on climate change, significantly reduced the impact of the HP models. Finally, the effect of the electricity mix was examined. The applied static electricity mix seemed to be a slight underestimation of the actual environmental impact. The high impact of the current electricity mix underscores the importance of integrating more renewable sources into the mix, which would significantly lower the impact of scenarios utilizing electricity as an energy source.

6.2 Recommendations For Future Research

This study, performed an LCA starting from the use case *The Schipjes*. This neighborhood consists of several small buildings and is not necessarily representative for other districts. Larger buildings seemed to be more beneficial for heat pump scenarios and might offer interesting results. Therefore, a similar study, considering a larger district or a neighborhood with larger buildings might offer different results, closer to reality.

Several assumptions had to be made regarding the heat pump models and the energy calculation methods. A more detailed analysis of the impact of various refrigerants and heat pumps can be conducted. Determining more relationships between different heat pump types, manufacturers, mass and their environmental impact. The high environmental impact of the heat pump installations also formulates an incentive towards manufacturers, to improve this. A more detailed analysis with an energy calculation method for each scenario, might provide more representative results on the impact of each scenario. Especially, considering the large impact of the HP models and energy use. A more detailed analysis of the impact of various refrigerants and heat pumps can be conducted. Determining more relationships between different heat pump types, manufacturers, mass and their environmental impact. The high environmental impact of the heat pump installations also formulates an incentive towards manufacturers, to improve this.

Because of the low impact of the distribution network, a higher insulated heating network can be opted for instead. This way, the trade-off between the material impact and the distribution heat loss can be optimized. If the distribution heat loss can be minimized, or if the heating network can work at lower temperatures, also reducing the heat loss, the potential for collective heating systems, to recover residual heat from industries can be examined further.

The impact of different electricity mixes can be investigated, integrating different impact indicators. If the impact of the electricity can be reduced, electrification of the heating systems will become even more interesting. This way, apart from improvements in efficiency, also the environmental impact per MJ can be reduced.

Finally, this study only focussed on the environmental impact of different heating systems. Integrating economic and comfort factors in the analysis might unlock more comprehensive results, which can give future research more directive, regarding which scenario has the most potential.

Appendices

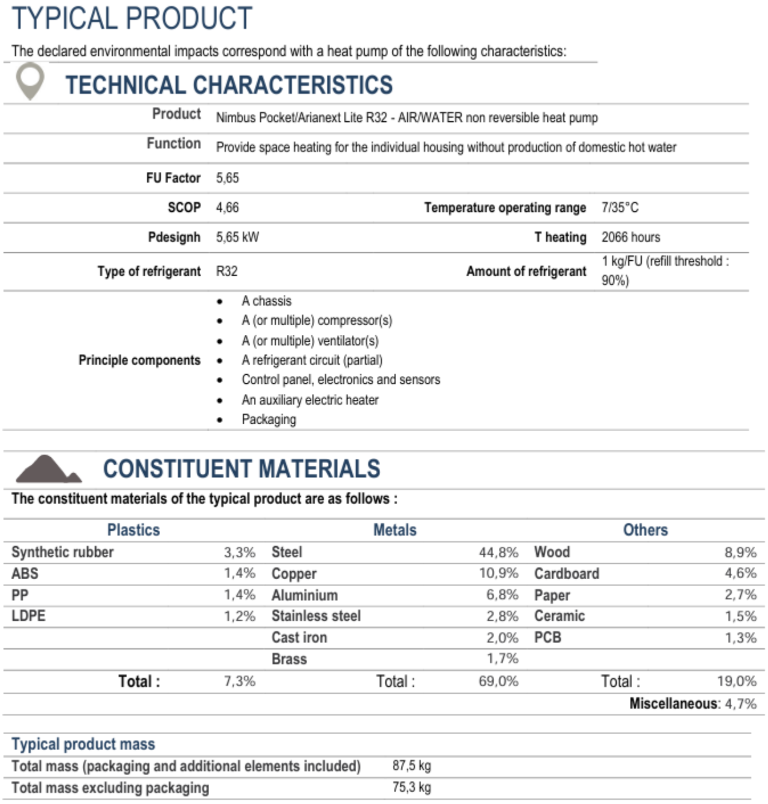
Appendix A

Component Data sheets

In this section, the most important information from the data sheets of the technical installations, more specifically the heat pumps, is gathered.

A.1 Heat pumps

ASHP Ariston (Nimbus Pocket/Arianext Lite R32)



TYPICAL PRODUCT

The declared environmental impacts correspond with a heat pump of the following characteristics:

TECHNICAL CHARACTERISTICS

Product	Nimbus Pocket/Arianext Lite R32 - AIR/WATER non reversible heat pump		
Function	Provide space heating for the individual housing without production of domestic hot water		
FU Factor	5,65		
SCOP	4,66	**Temperature operating range**	7/35°C
Pdesignh	5,65 kW	**T heating**	2066 hours
Type of refrigerant	R32	**Amount of refrigerant**	1 kg/FU (refill threshold : 90%)
Principle components	• A chassis • A (or multiple) compressor(s) • A (or multiple) ventilator(s) • A refrigerant circuit (partial) • Control panel, electronics and sensors • An auxiliary electric heater • Packaging		

CONSTITUENT MATERIALS

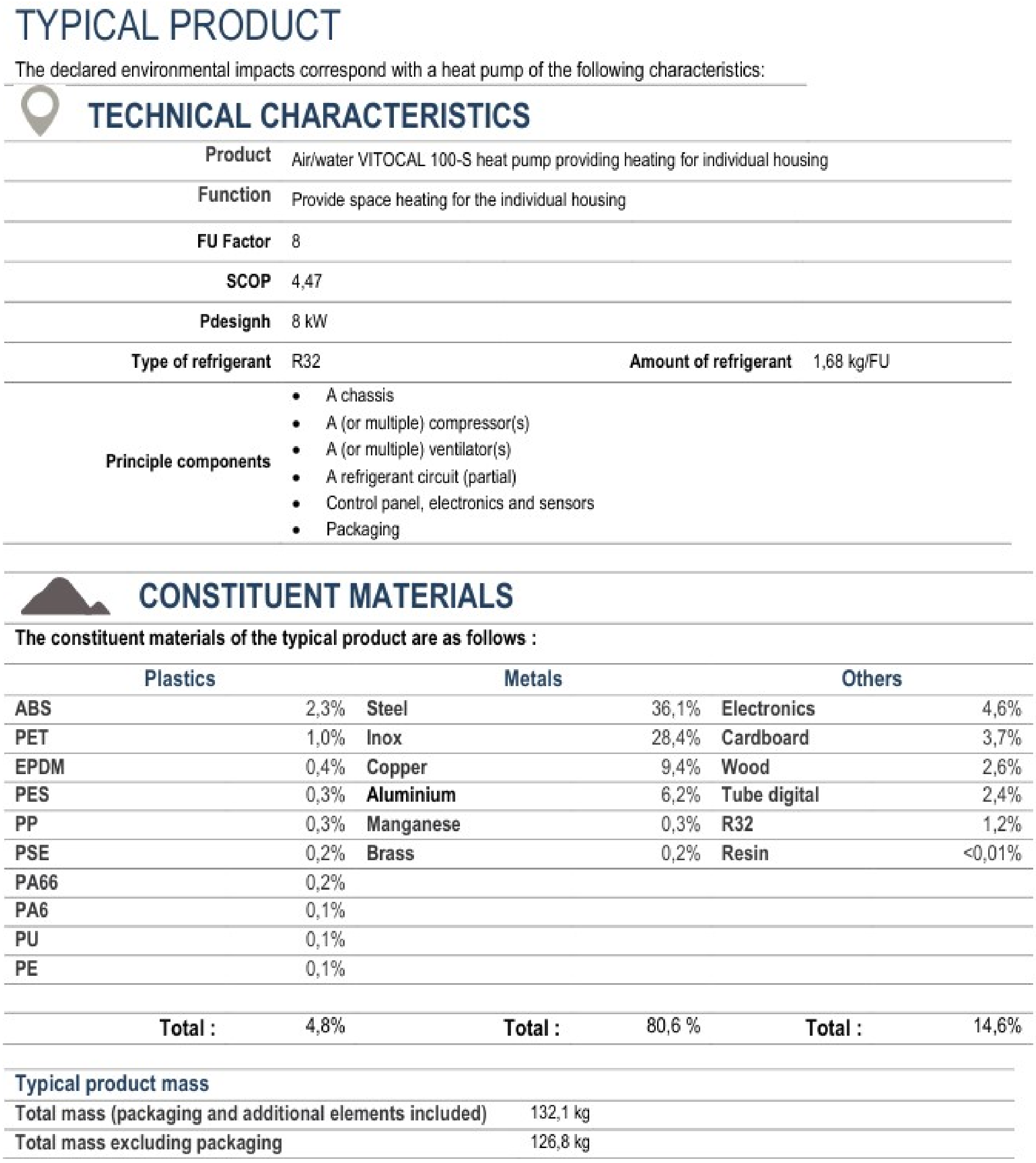
The constituent materials of the typical product are as follows :

Plastics		Metals		Others	
Synthetic rubber	3,3%	**Steel**	44,8%	**Wood**	8,9%
ABS	1,4%	**Copper**	10,9%	**Cardboard**	4,6%
PP	1,4%	**Aluminium**	6,8%	**Paper**	2,7%
LDPE	1,2%	**Stainless steel**	2,8%	**Ceramic**	1,5%
		Cast iron	2,0%	**PCB**	1,3%
		Brass	1,7%		
Total :	7,3%	Total :	69,0%	Total :	19,0%
				Miscellaneous:	4,7%

Typical product mass	
Total mass (packaging and additional elements included)	87,5 kg
Total mass excluding packaging	75,3 kg

Figure A.1: Technical characteristics and Material list from data sheet Ariston (copied from [7])

ASHP Viessmann (Vitocal 100-S)



TYPICAL PRODUCT

The declared environmental impacts correspond with a heat pump of the following characteristics:

TECHNICAL CHARACTERISTICS

Product	Air/water VITOCAL 100-S heat pump providing heating for individual housing		
Function	Provide space heating for the individual housing		
FU Factor	8		
SCOP	4,47		
Pdesignh	8 kW		
Type of refrigerant	R32	**Amount of refrigerant**	1,68 kg/FU
Principle components	• A chassis • A (or multiple) compressor(s) • A (or multiple) ventilator(s) • A refrigerant circuit (partial) • Control panel, electronics and sensors • Packaging		

CONSTITUENT MATERIALS

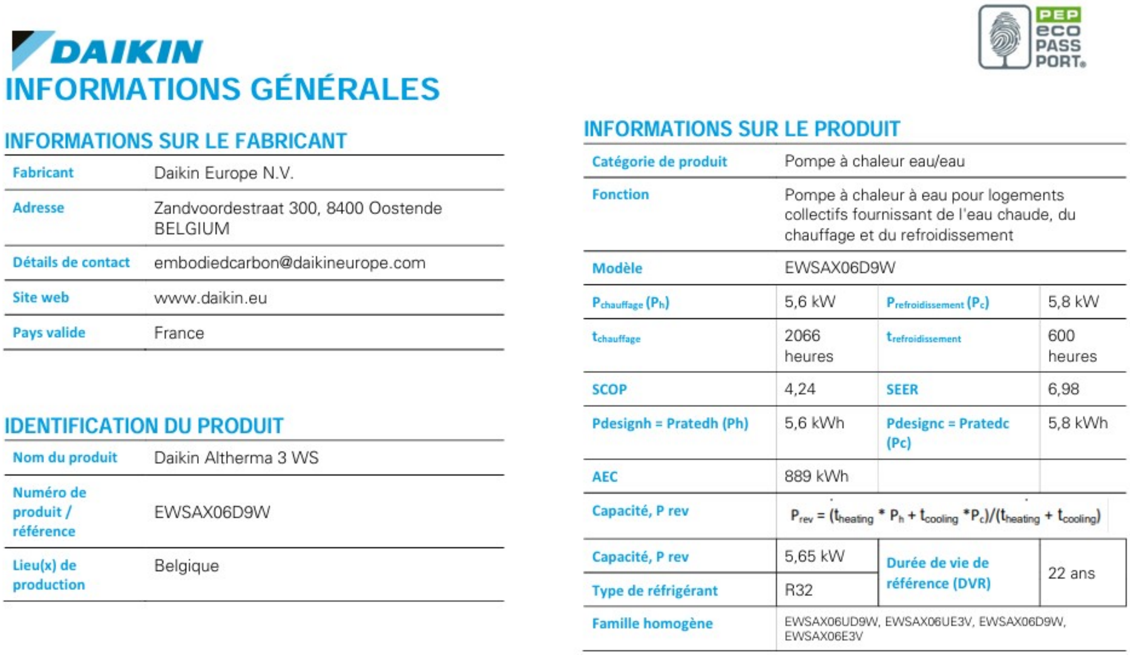
The constituent materials of the typical product are as follows :

Plastics		Metals		Others	
ABS	2,3%	**Steel**	36,1%	**Electronics**	4,6%
PET	1,0%	**Inox**	28,4%	**Cardboard**	3,7%
EPDM	0,4%	**Copper**	9,4%	**Wood**	2,6%
PES	0,3%	**Aluminium**	6,2%	**Tube digital**	2,4%
PP	0,3%	**Manganese**	0,3%	**R32**	1,2%
PSE	0,2%	**Brass**	0,2%	**Resin**	<0,01%
PA66	0,2%				
PA6	0,1%				
PU	0,1%				
PE	0,1%				
Total :	4,8%	**Total :**	80,6 %	**Total :**	14,6%

Typical product mass	
Total mass (packaging and additional elements included)	132,1 kg
Total mass excluding packaging	126,8 kg

Figure A.2: Technical characteristics and material list from data sheet Viessmann (copied from [8])

GSHP Daikin (Daikin Altherma 3 WS)



DAIKIN

INFORMATIONS GÉNÉRALES

INFORMATIONS SUR LE FABRICANT

Fabricant	Daikin Europe N.V.
Adresse	Zandvoordestraat 300, 8400 Oostende BELGIUM
Détails de contact	embodiedcarbon@daikineurope.com
Site web	www.daikin.eu
Pays valide	France

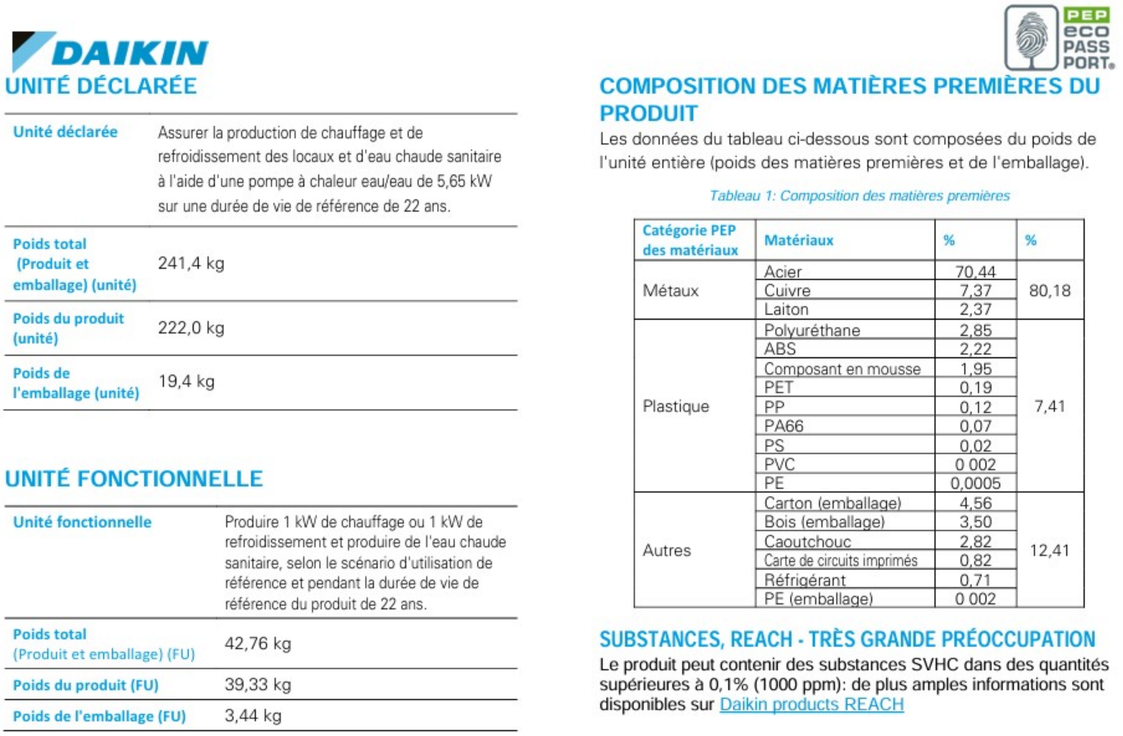
IDENTIFICATION DU PRODUIT

Nom du produit	Daikin Altherma 3 WS
Numéro de produit / référence	EWSAX06D9W
Lieu(x) de production	Belgique

INFORMATIONS SUR LE PRODUIT

Catégorie de produit	Pompe à chaleur eau/eau		
Fonction	Pompe à chaleur à eau pour logements collectifs fournissant de l'eau chaude, du chauffage et du refroidissement		
Modèle	EWSAX06D9W		
$P_{chauffage}$ (P_h)	5,6 kW	**$P_{refroidissement}$ (P_c)**	5,8 kW
$t_{chauffage}$	2066 heures	**$t_{refroidissement}$**	600 heures
SCOP	4,24	**SEER**	6,98
Pdesignh = Pratedh (Ph)	5,6 kWh	**Pdesignc = Pratedc (Pc)**	5,8 kWh
AEC	889 kWh		
Capacité, P rev	$P_{rev} = (t_{heating} * P_h + t_{cooling} * P_c)/(t_{heating} + t_{cooling})$		
Capacité, P rev	5,65 kW	**Durée de vie de référence (DVR)**	22 ans
Type de réfrigérant	R32		
Famille homogène	EWSAX06UD9W, EWSAX06UE3V, EWSAX06D9W, EWSAX06E3V		

FIGURE A.3: Technical characteristics from data sheet Daikin (copied from [9])



DAIKIN

UNITÉ DÉCLARÉE

Unité déclarée	Assurer la production de chauffage et de refroidissement des locaux et d'eau chaude sanitaire à l'aide d'une pompe à chaleur eau/eau de 5,65 kW sur une durée de vie de référence de 22 ans.
Poids total (Produit et emballage) (unité)	241,4 kg
Poids du produit (unité)	222,0 kg
Poids de l'emballage (unité)	19,4 kg

UNITÉ FONCTIONNELLE

Unité fonctionnelle	Produire 1 kW de chauffage ou 1 kW de refroidissement et produire de l'eau chaude sanitaire, selon le scénario d'utilisation de référence et pendant la durée de vie de référence du produit de 22 ans.
Poids total (Produit et emballage) (FU)	42,76 kg
Poids du produit (FU)	39,33 kg
Poids de l'emballage (FU)	3,44 kg

COMPOSITION DES MATIÈRES PREMIÈRES DU PRODUIT

Les données du tableau ci-dessous sont composées du poids de l'unité entière (poids des matières premières et de l'emballage).

Tableau 1: Composition des matières premières

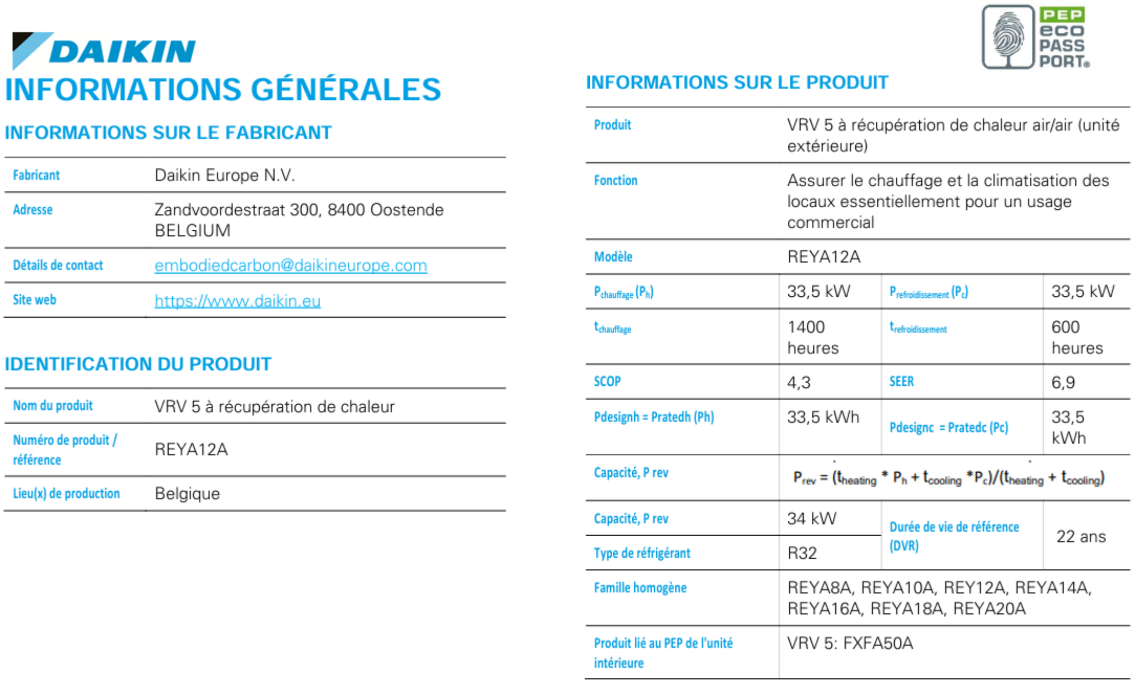
Catégorie PEP des matériaux	Matériaux	%	%
Métaux	Acier	70,44	80,18
	Cuivre	7,37	
	Laiton	2,37	
Plastique	Polyuréthane	2,85	7,41
	ABS	2,22	
	Composant en mousse	1,95	
	PET	0,19	
	PP	0,12	
	PA66	0,07	
	PS	0,02	
	PVC	0 002	
	PE	0,0005	
Autres	Carton (emballage)	4,56	12,41
	Bois (emballage)	3,50	
	Caoutchouc	2,82	
	Carte de circuits imprimés	0,82	
	Réfrigérant	0,71	
	PE (emballage)	0 002	

SUBSTANCES, REACH - TRÈS GRANDE PRÉOCCUPATION

Le produit peut contenir des substances SVHC dans des quantités supérieures à 0,1% (1000 ppm): de plus amples informations sont disponibles sur Daikin products REACH

FIGURE A.4: Material list from data sheet Daikin (copied from [10])

Collective GSHP Daikin (VRV 5)



DAIKIN

INFORMATIONS GÉNÉRALES

INFORMATIONS SUR LE FABRICANT

Fabricant	Daikin Europe N.V.
Adresse	Zandvoordestraat 300, 8400 Oostende BELGIUM
Détails de contact	embodiedcarbon@daikineurope.com
Site web	https://www.daikin.eu

IDENTIFICATION DU PRODUIT

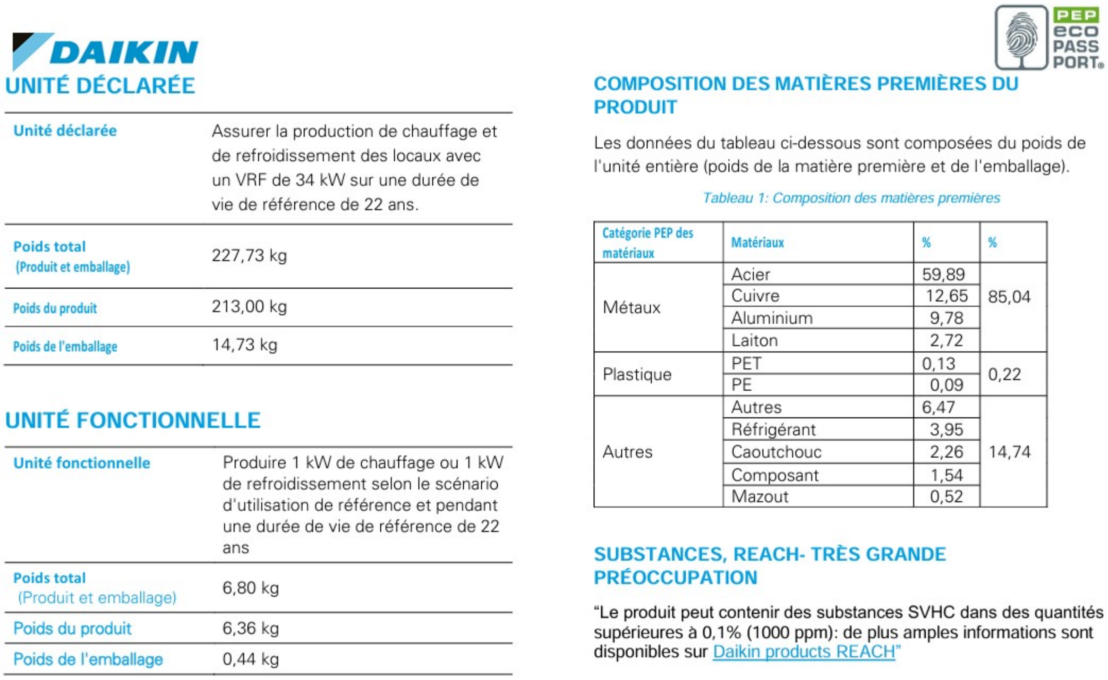
Nom du produit	VRV 5 à récupération de chaleur
Numéro de produit / référence	REYA12A
Lieu(x) de production	Belgique

PEP eco PASS PORT®

INFORMATIONS SUR LE PRODUIT

Produit	VRV 5 à récupération de chaleur air/air (unité extérieure)		
Fonction	Assurer le chauffage et la climatisation des locaux essentiellement pour un usage commercial		
Modèle	REYA12A		
$P_{chauffage}$ (P_h)	33,5 kW	**$P_{refroidissement}$ (P_c)**	33,5 kW
$t_{chauffage}$	1400 heures	**$t_{refroidissement}$**	600 heures
SCOP	4,3	**SEER**	6,9
Pdesignh = Pratedh (Ph)	33,5 kWh	**Pdesignc = Pratedc (Pc)**	33,5 kWh
Capacité, P rev	$P_{rev} = (\dot{t}_{heating} * P_h + t_{cooling} * P_c)/(\dot{t}_{heating} + t_{cooling})$		
Capacité, P rev	34 kW	**Durée de vie de référence (DVR)**	22 ans
Type de réfrigérant	R32		
Famille homogène	REYA8A, REYA10A, REY12A, REYA14A, REYA16A, REYA18A, REYA20A		
Produit lié au PEP de l'unité intérieure	VRV 5: FXFA50A		

Figure A.5: Technical characteristics from data sheet Daikin (copied from [11])



DAIKIN

UNITÉ DÉCLARÉE

Unité déclarée	Assurer la production de chauffage et de refroidissement des locaux avec un VRF de 34 kW sur une durée de vie de référence de 22 ans.
Poids total (Produit et emballage)	227,73 kg
Poids du produit	213,00 kg
Poids de l'emballage	14,73 kg

UNITÉ FONCTIONNELLE

Unité fonctionnelle	Produire 1 kW de chauffage ou 1 kW de refroidissement selon le scénario d'utilisation de référence et pendant une durée de vie de référence de 22 ans
Poids total (Produit et emballage)	6,80 kg
Poids du produit	6,36 kg
Poids de l'emballage	0,44 kg

PEP eco PASS PORT®

COMPOSITION DES MATIÈRES PREMIÈRES DU PRODUIT

Les données du tableau ci-dessous sont composées du poids de l'unité entière (poids de la matière première et de l'emballage).

Tableau 1: Composition des matières premières

Catégorie PEP des matériaux	Matériaux	%	%
Métaux	Acier	59,89	85,04
	Cuivre	12,65	
	Aluminium	9,78	
	Laiton	2,72	
Plastique	PET	0,13	0,22
	PE	0,09	
Autres	Autres	6,47	14,74
	Réfrigérant	3,95	
	Caoutchouc	2,26	
	Composant	1,54	
	Mazout	0,52	

SUBSTANCES, REACH- TRÈS GRANDE PRÉOCCUPATION

"Le produit peut contenir des substances SVHC dans des quantités supérieures à 0,1% (1000 ppm): de plus amples informations sont disponibles sur Daikin products REACH"

Figure A.6: Material list from data sheet Daikin (copied from [11])

Collective GSHP Viessmann (Vitocal 300-G BWS 301.A45)

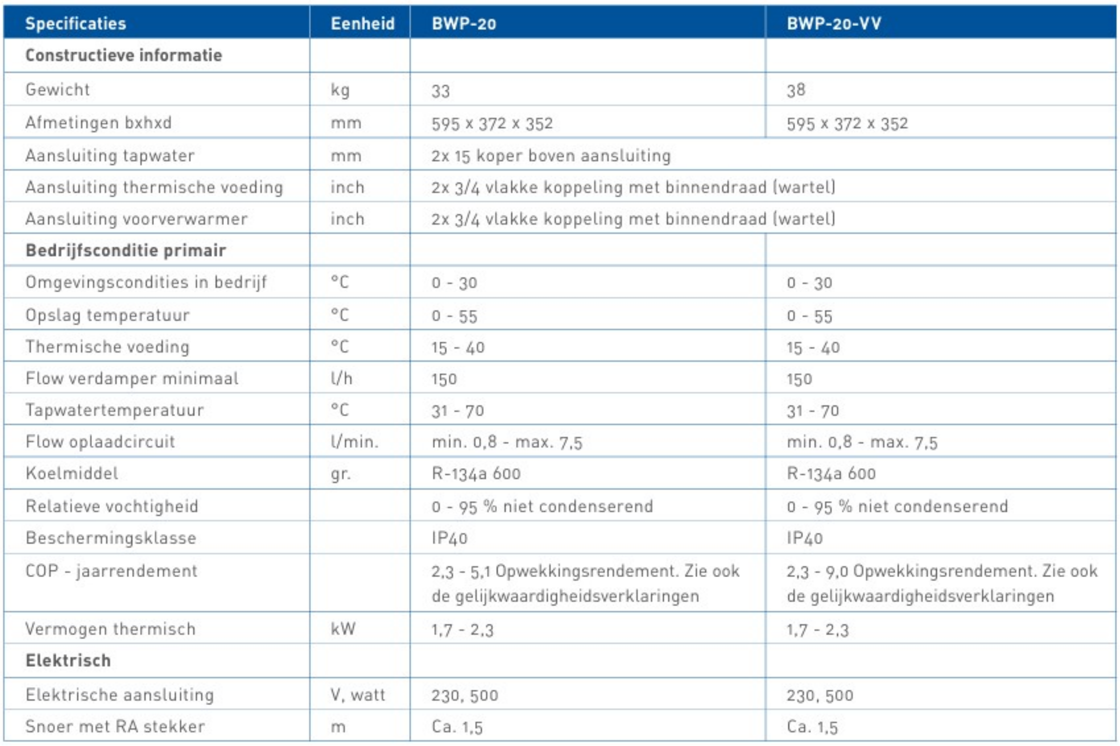
In the collective heating system of *De Schipjes*, the heat pump from Viessmann, the type 301.A45, is integrated, with a nominal heating power of 42.8kW.

Type BW/BWS		**301.A21**	**301.A29**	**301.A45**
Vermogensgegevens conform EN 14511 (B0/W35, spreiding 5 K)				
Nom. vermogen	kW	21,2	28,8	42,8
Koelvermogen	kW	17,0	23,3	34,2
Elektr. opgenomen vermogen	kW	4,48	5,96	9,28
Prestatiecoëfficiënt ε (COP)		4,73	4,83	4,60
Brijn (primair circuit)				
Inhoud	l	6,5	8,5	11,5
Min. debiet	l/h	3300	4200	6500
Doorstroomweerstand	mbar	70	95	154
	kPa	7	9,5	15,4
Max. aanvoertemperatuur (brijninlaat)	°C	25	25	25
Min. aanvoertemperatuur (brijninlaat)	°C	–10	–10	–10
Verwarmingswater (secundair circuit)				
Inhoud	l	6,5	8,5	11,5
Min. debiet (10K spreiding)	l/h	1900	2550	3700
Doorstroomweerstand	mbar	38	38	65
	kPa	3,8	3,8	6,5
Max. aanvoertemperatuur	°C	60	60	60
Elektrische waarden warmtepomp				
Nominale spanning compressor	V	3/PE 400 V/50 Hz		
Nominale stroom compressor	A	16	22	34
Aanloopstroom compressor (met aanloopstroombegrenzing)	A	< 30	41	47
Aanloopstroom compressor bij geblokkeerde rotor	A	95	118	174
Zekering compressor	A	1 x C16A	1 x C25A	1 x C40A
		3-polig	3-polig	3-polig
Beschermingsklasse		I	I	I
Elektrische waarden regeling				
Nominale spanning regeling/elektronica	V	1/N/PE 230 V/50 Hz		
Zekering regeling/elektronica		1 x B16A		
Zekering regeling/elektronica	A	T 6,3 A/250 V		
Max. elektr. vermogensopname regeling/elektronica warmtepomp 1e trap (type BW 301.A)	W	25	25	25
Max. elektr. vermogensopname regeling/elektronica warmtepomp 2e trap (type BWS 301.A)		20	20	20
Elektr. vermogensopname regeling/elektronica 1e en 2e trap	W	45	45	45
Beschermingstype		IP 20	IP 20	IP 20
Koelcircuit				
Werkmedium		R410A	R410A	R410A
– Vulhoeveelheid	kg	4,7	6,2	7,7
– Broeikaspotentieel		2088	2088	2088
– CO_2-equivalent	t	9,81	12,96	16,08
Toegest. werkdruk hogedrukzijde	bar	43	43	43
	MPa	4,3	4,3	4,3
Toegel. bedrijfsdruk lagedrukzijde	bar	28	28	28
	MPa	2,8	2,8	2,8
Compressor	Type	Scroll hermetisch gesloten		
Olie in compressor	Type	Emkarate RL32 3MAF		
Toegel. bedrijfsdruk				
Primair circuit	bar	3	3	3
	MPa	0,3	0,3	0,3
Secundair circuit	bar	3	3	3
	MPa	0,3	0,3	0,3
Afmetingen				
Totale lengte	mm	1085	1085	1085
Totale breedte	mm	780	780	780
Totale hoogte zonder bedieningseenheid	mm	1074	1074	1074
Totale hoogte (bedieningseenheid opengeklapt, alleen type BW 301.A)	mm	1267	1267	1267
Gewicht				
Warmtepomp 1e trap (type BW 301.A)	kg	245	272	298
Warmtepomp 2de trap (type BWS 301.A)	kg	240	267	293

Figure A.7: Material list from data sheet Viessmann (copied from [12])

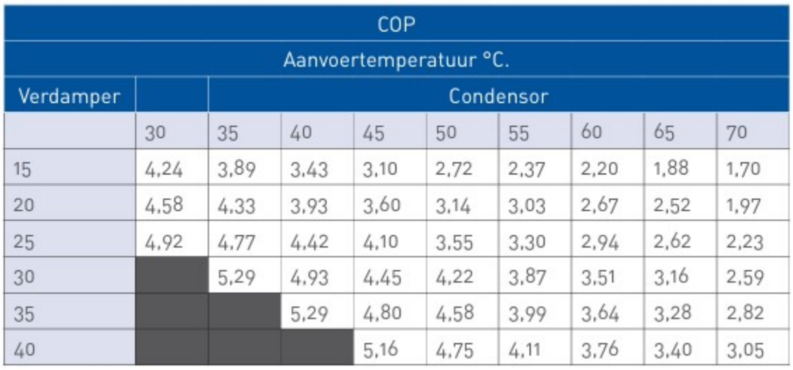
BHP Ithodaalderop (BWP-20-VV)

In the collective heating system of *De Schipjes*, the BWP-20-VV is utilized as BHP. The difference between both types is the possibility for preheating, indicated by the '-VV'.



Specificaties	Eenheid	BWP-20	BWP-20-VV
Constructieve informatie			
Gewicht	kg	33	38
Afmetingen bxhxd	mm	595 x 372 x 352	595 x 372 x 352
Aansluiting tapwater	mm	2x 15 koper boven aansluiting	
Aansluiting thermische voeding	inch	2x 3/4 vlakke koppeling met binnendraad (wartel)	
Aansluiting voorverwarmer	inch	2x 3/4 vlakke koppeling met binnendraad (wartel)	
Bedrijfsconditie primair			
Omgevingscondities in bedrijf	°C	0 - 30	0 - 30
Opslag temperatuur	°C	0 - 55	0 - 55
Thermische voeding	°C	15 - 40	15 - 40
Flow verdamper minimaal	l/h	150	150
Tapwatertemperatuur	°C	31 - 70	31 - 70
Flow oplaadcircuit	l/min.	min. 0,8 - max. 7,5	min. 0,8 - max. 7,5
Koelmiddel	gr.	R-134a 600	R-134a 600
Relatieve vochtigheid		0 - 95 % niet condenserend	0 - 95 % niet condenserend
Beschermingsklasse		IP40	IP40
COP - jaarrendement		2,3 - 5,1 Opwekkingsrendement. Zie ook de gelijkwaardigheidsverklaringen	2,3 - 9,0 Opwekkingsrendement. Zie ook de gelijkwaardigheidsverklaringen
Vermogen thermisch	kW	1,7 - 2,3	1,7 - 2,3
Elektrisch			
Elektrische aansluiting	V, watt	230, 500	230, 500
Snoer met RA stekker	m	Ca. 1,5	Ca. 1,5

Figure A.8: Technical characteristics from data sheet Ithodaalderop (copied from [13])



COP									
Aanvoertemperatuur °C.									
Verdamper		Condensor							
	30	35	40	45	50	55	60	65	70
15	4,24	3,89	3,43	3,10	2,72	2,37	2,20	1,88	1,70
20	4,58	4,33	3,93	3,60	3,14	3,03	2,67	2,52	1,97
25	4,92	4,77	4,42	4,10	3,55	3,30	2,94	2,62	2,23
30		5,29	4,93	4,45	4,22	3,87	3,51	3,16	2,59
35			5,29	4,80	4,58	3,99	3,64	3,28	2,82
40				5,16	4,75	4,11	3,76	3,40	3,05

Figure A.9: COP characteristics from data sheet Ithodaalderop (copied from [13])

Appendix B

Collective Heating Network

B.1 Individual Part

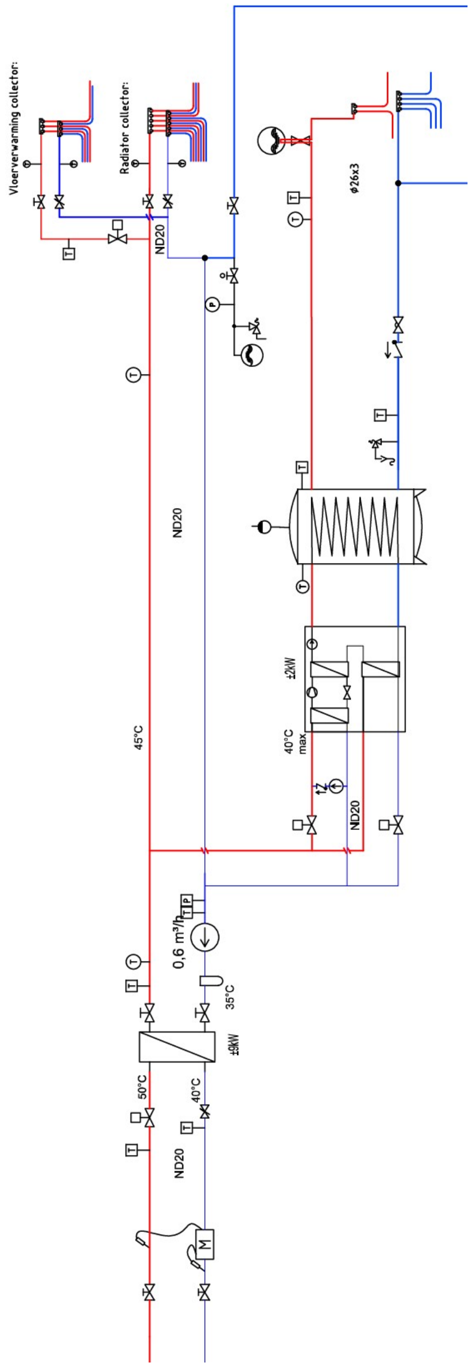


Figure B.1: Collective heating system - Individual part (copied from [14])

B.2 Generation Part

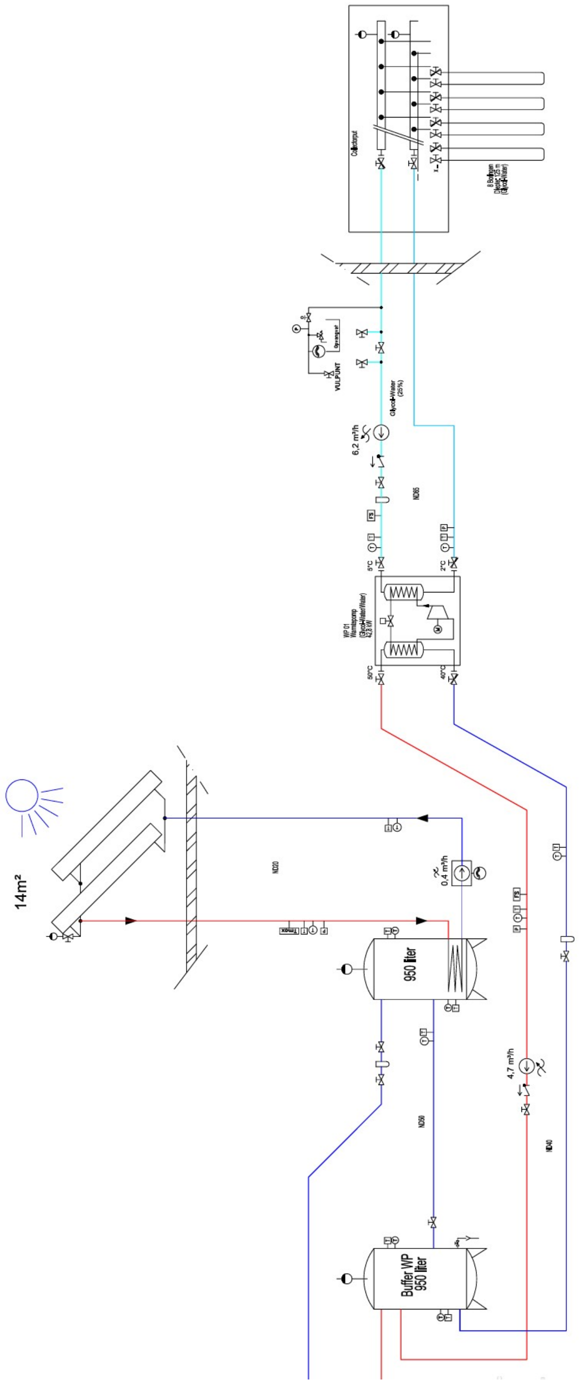


FIGURE B.2: Generation part (copied from [14])

Bibliography

[1] A. C. Violante, F. Donato, G. Guidi, and M. Proposito, "Comparative life cycle assessment of the ground source heat pump vs air source heat pump," *Renewable Energy*, vol. 188, pp. 1029–1037, 2022.

[2] L. H. Jelfger Janssen, "Assessing and improving the control of a small-scale fully renewables-based low-temperature thermal network in the historic city center of bruges." Retrieved on 08/05/2024 from `https://www.boydens.be/be/projects/wonen/de-schipjes-godshuizen/`, 2019.

[3] B. engineering (Sweco), "De schipjes godshuizen brugge, belgium, europa." Retrieved on 08/05/2024 from `https://www.boydens.be/be/projects/wonen/de-schipjes-godshuizen/`, 2017.

[4] J. Jansen, F. Jorissen, and L. Helsen, "Optimal control of a fourth generation district heating network using an integrated non linear model predictive controller," *Applied Thermal Engineering*, vol. 223, p. 120030, 2023.

[5] engineers from TOTEM, "Environmental profile of building elements [update 2021]," 2021.

[6] I. S. of Automation, "Why is co2 the most promising refrigerant in the industry." Retrieved from `https://blog.isa.org/why-co2-is-the-most-promising-refrigerant-in-the-cooling-industry#:~:text=The%20physical%20properties%20of%20CO2,can%20remain%20at%20low%20temperatures.` on 18/05/2024, 2024.

[7] Ariston, "Product environmental profile, air/water heat pump nimbus pocket/arianext lite r32 50, providing heating and production for individual dwelling," tech. rep., Ariston, 2023.

[8] Viessmann, "Product environmental profile air/water vitocal 100s heat pump providing heating for individual housing," tech. rep., Viessmann, 2023.

[9] D. E. N.V., "Profil environnemental produit pompe a chaleur air/eau, chauffage et eau chaude sanitaire, daikin altherma 3 r 180l, fluide r32," tech. rep., DAIKIN EUROPE N.V., 2022.

[10] D. E. N.V., "Profil environnemental produit (pep), conformement aux normes en 15804+a2 and ise 14025/iso21930, daikin altherma 3 ws," tech. rep., DAIKIN EUROPE N.V., 2023.

[11] D. E. N.V., "Profil environnemental produit (pep), conformement aux normes en 15804+a2 and ise 14025/iso21930, vrv 5 a recuperatin de chaleur air/air," tech. rep., DAIKIN EUROPE N.V., 2023.

[12] Viessmann, "Vitocal 300g, type bw 301.a21 tot a45, bws 301.a21 tot a45," tech. rep., Viessmann.

[13] Ithodaalderop, "Booster warmte pomp bwp-20, bwp-20-vv," tech. rep., Ithodaalderop.

[14] Celcio, "Hydraulisch schema reva," tech. rep., Celcio, 2021.

[15] D. Trigaux, "Elaboration of a sustainability assessment method for neighbourhoods," 2017 12 15.

[16] F. E. A. (VEA), "Energieprestatiecertificaten voor bestaande residentiele gebouwen in vlaanderen," 2013.

[17] M. Nedergaard, "Default emission factors." Retrieved on 31/05/2024 from `https://github.com/electricitymaps/electricitymaps-contrib/wiki/Default-emission-factors`, 2024.

[18] M. Herczeg, D. McKinnon, L. Milios, I. Bakas, E. Klaassens, K. Svatikova, and O. Widerberg, "Resource efficiency in the building sector," *Final Report*, 2014.

[19] U. Sbci, "Buildings and climate change: Summary for decision makers," *United Nations Environmental Programme, Sustainable Buildings and Climate Initiative, Paris*, vol. 1, p. 62, 2009.

[20] E. C. Eurostat, "Heat pumps." Retrieved on 24/12/2023 from `https://energy.ec.europa.eu/topics/energy-efficiency/heat-pumps_en`, (2023).

[21] E. Comission, "Energy, climate change, environment." Retrieved on 14/10/2023 from `https://commission.europa.eu/energy-climate-change-environment_en`, (2023).

[22] S. Universidades, "What is sustainability? definition, types and examples." Retrieved on 12/10/2023 from `https://www.santanderopenacademy.com/en/blog/what-is-sustainability.html`.

[23] J. P. J. N. Markovska, V. Taseska, "Swot analyses of the national energy sector for sustainable energy development." Retrieved on 14/10/2023 from `https://www.sciencedirect.com/science/article/pii/S0360544209000450`, (2009).

[24] V. Tobias and A. Karen, "Ontwerp en milieu-impactanalyse van hvac systemen in de vroege ontwerpfase voor kantoorgebouwen," 2021.

[25] H. Lin, J. Clavreul, C. Jeandaux, J. Crawley, and I. Butnar, "Environmental life cycle assessment of heating systems in the uk: Comparative assessment of hybrid heat pumps vs. condensing gas boilers," *Energy and Buildings*, vol. 240, p. 110865, 2021.

[26] I. Sarbu and C. Sebarchievici, "Performance evaluation of radiator and radiant floor heating systems for an office room connected to a ground coupled heat pump," *Energies*, vol. 9, no. 4, 2016.

[27] A. H. Fard, P. E. Nejad, Z. Aidoun, and M. Ouzzane, "A techno economic comparison of a direct expansion ground source and an air source heat pump system in canadian cold climates," *Energy*, vol. 87, pp. 49–59, 2015.

[28] D. I. E. Union, "Different generations of dhc." Retrieved on 26/11/2023 from `https://5gdhc.eu/differentgenerationsofdhc/`, 2023.

[29] J. Famiglietti, L. Gerevini, G. Spirito, M. Pozzi, A. Denarie, R. Scoccia, and M. Motta, "Environmental life cycle assessment scenarios for a district heating network. an italian case study," *Energy Reports*, vol. 7, pp. 368–379, 2021.

[30] S. Frederiksen and Werner, *District heating and cooling.* Lund: Studentlitteratur, 2014.

[31] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund, and B. V. Mathiesen, "4th generation district heating (4gdh): Integrating smart thermal grids into future sustainable energy systems," *Energy*, vol. 68, pp. 1–11, 2014.

[32] H. Lund, P. A. Ostergaard, T. B. Nielsen, S. Werner, J. E. Thorsen, O. Gudmundsson, A. Arabkoohsar, and B. V. Mathiesen, "Perspectives on fourth and fifth generation district heating," *Energy*, vol. 227, p. 120520, 2021.

[33] R. Lund and U. Persson, "Mapping of potential heat sources for heat pumps for district heating in denmark," *Energy*, vol. 110, pp. 129–138, 2016. Special issue on Smart Energy Systems and 4th Generation District Heating.

[34] A. Jodeiri, M. Goldsworthy, S. Buffa, and M. Cozzini, "Role of sustainable heat sources in transition towards fourth generation district heating, a review," *Renewable and Sustainable Energy Reviews*, vol. 158, pp. 112–156, 2022.

[35] K. Holmgren, "Role of a district heating network as a user of waste heat supply from various sources the case of goteborg," *Applied Energy*, vol. 83, no. 12, pp. 1351–1367, 2006.

[36] A. Jodeiri, M. Goldsworthy, S. Buffa, and M. Cozzini, "Role of sustainable heat sources in transition towards fourth generation district heating, a review," *Renewable and Sustainable Energy Reviews*, vol. 158, pp. 112–156, 2022.

[37] L. H., Z. H. R., L. T., and F. W., "Thermal performance of three horizontal ground heat exchanger systems: comparison of linear-loop, spiral-coil and slinky-coil arrangements," *Frontiers in Energy Research*, vol. 11, 2023.

[38] T. Earth, "Ground source heat pumps: How much space do you need?." Retreived on 10/04/2024 from `https://www.thermalearth.co.uk/blog/how-much-space-for-a-ground-source-heat-pump`.

[39] G. Hou, H. Taherian, Y. Song, W. Jiang, and D. Chen, "A systematic review on optimal analysis of horizontal heat exchangers in ground source heat pump systems," *Renewable and Sustainable Energy Reviews*, vol. 154, 2022.

[40] T. Sliwa, A. Sapinska sliwa, A. Gonet, T. Kowalski, and A. Sojczynska, "Geothermal boreholes in poland, overview of the current state of knowledge," *Energies*, vol. 14, no. 11, 2021.

[41] T. Kaya and P. Hoshan, *Corrosion and material selection for geothermal systems*, vol. 2005. 2005.

[42] S. L. Bergen, L. Zemberekci, and S. D. Nair, "A review of conventional and alternative cementitious materials for geothermal wells," *Renewable and Sustainable Energy Reviews*, vol. 161, p. 112347, 2022.

[43] E. Bett, *Geothermal well cementing, materials and placement techniques.* LAP LAMBERT Academic Publishing, 2017.

[44] G. Emmi, A. Zarrella, M. De Carli, M. Dona, and A. Galgaro, "Energy performance and cost analysis of some borehole heat exchanger configurations with different heat carrier fluids in mild climates," *Geothermics*, vol. 65, pp. 158–169, 2017.

[45] Anonymous, "Heat pumps." Retrieved on 24/12/2023 from `https://en.wikipedia.org/wiki/Heat_pump`.

[46] L. Evangelisti, R. De Lieto Vollaro, and F. Asdrubali, "Latest advances on solar thermal collectors: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 114, p. 109318, 2019.

[47] S. Square, "Thermal solar energy collectors: Types, uses, and components." Retrieved on 24/12/2023 from `https://www.solarsquare.in/blog/solar-energy-collectors/`, 08/2022.

[48] B. Wang, J. J. Klemes, N. Li, M. Zeng, P. S. Varbanov, and Y. Liang, "Heat exchanger network retrofit with heat exchanger and material type selection: A review and a novel method," *Renewable and Sustainable Energy Reviews*, vol. 138, p. 110479, 2021.

[49] T. Axsom, "Heat exchanger material selection." retreived on 20/11/2023 from `https://www.fictiv.com/articles/heatexchangermaterialselection`, 2023.

[50] Madrass, "Heat exchanger insulation jackets." Retreived on 20/11/2023 from `https://mattress-insulation.com/heat-exchanger-insulation-jackets/`, 2023.

[51] ThermaXX, "Heat exchanger insulation jackets." Retreived on 20/11/2023 from `https://www.thermaxxjackets.com/products/hotpipevalveequipmentinsulation/heatexchangerinsulationjackets/`, 2023.

[52] B. P. F. Pipes, "District heating systems, guidance notes." Retrieved on 8/11/2023 from `https://www.bpfpipesgroup.com/media/62311/District-Heating-Systems-v2.pdf`, 2017.

[53] M. Limited, "Why plastic pipes for district heating?." Retrieved on 8/11/2023 from `https://mibec.co.uk/why-plastic-pipes-for-district-heating/#:~:text=Plastic%20pre%2Dinsulated%20pipes%20also,have%20a%20longer%20service%20life.`, 2020.

[54] M. Kayfeci, "Determination of energy saving and optimum insulation thicknesses of the heating piping systems for different insulation materials," *Energy and Buildings*, vol. 69, pp. 278–284, 2014.

[55] D. B. K. R., "Antifreeze acceptability for ground coupled heat pump ground loops in the united states," *ASHRAE Transactions*, vol. 104, p. 938, 1998.

[56] H. E. W., W. M. W., B. A. N., and T. R. E., "Assessment of antifreeze solutions for ground source heat pump systems," *ASHRAE Transactions*, vol. 103, p. 747, 1997.

[57] A. Dinker, M. Agarwal, and G. Agarwal, "Heat storage materials, geometry and applications: A review," *Journal of the Energy Institute*, vol. 90, no. 1, pp. 1–11, 2017.

[58] W. Villasmil, L. J. Fischer, and J. Worlitschek, "A review and evaluation of thermal insulation materials and methods for thermal energy storage systems," *Renewable and Sustainable Energy Reviews*, vol. 103, pp. 71–84, 2019.

[59] S. D. D., H. C. E., P. Pujadas, A. de la Fuente, X. Gabarrell, J. Rieradevall, and A. Josa, "Environmental and geometric optimisation of cylindrical drinking water storage tanks," *Int J Life Cycle Assess*, vol. 20, pp. 1612–1624, 2015.

[60] H. style, "What material should your next radiator be made from?." Retrieved on 14/11/2023 from `https://www.tapwarehouse.com/blog/buying-guides/what-should-your-next-radiator-be-made-from#:~:text=Mild%20steel%20is%20by%20far,cheap%20to%20buy%20for%20you.`, 2019.

[61] G. Zhou and J. He, "Thermal performance of a radiant floor heating system with different heat storage materials and heating pipes," *Applied Energy*, vol. 138, pp. 648–660, 2015.

[62] Beama, "Beama Underfloor Heating, guide to types of UFH pipework," tech. rep., Beama, 2019.

[63] Verwarmingswinkel, "Vloerverwarming." Retrieved on 11/04/2024 from `https://www.verwarmingswinkel.nl/vloerverwarminghulp`, 2024.

[64] M. Gaudon, "5 best underfloor heating insulations." Retrieved on 16/11/2023 from `https://www.thefloorheatingwarehouse.co.uk/underfloor-heating-insulation/`, 2023.

[65] J. Liu and Z. Lin, "Energy and exergy performances of floor, ceiling, wall radiator and stratum ventilation heating systems for residential buildings," *Energy and Buildings*, vol. 220, p. 110046, 2020.

[66] C. Sebarchievici, D. Dan, and I. Sarbu, "Performance assessment of a ground coupled heat pump for an office room heating using radiator or radiant floor heating systems," *Procedia Engineering*, vol. 118, pp. 88–100, 2015. Defining the future of sustainability and resilience in design, engineering and construction.

[67] V. de Putteand Stijn, Himpe, E. Nonneman, J. Steeman, M. Janssens, and Arnold, "Assessment of the heat loss coefficient of a renovated historical dwelling using a co-heating test," *Journal of Physics: Conference Series*, vol. 2069, p. 012085, 11 2021.

[68] E. Kenhove, A. Aertgeerts, J. Laverge, and A. Janssens, "Energy efficient renovation of heritage residential buildings using modelica simulations," 12 2015.

[69] MakeEnergy, "Ground source heat pump borehole, the ultimate guide." Retrieved on 06/05/2024 from `https://makenergy.com/ground-source-heat-pump-borehole-guide/`, 2024.

[70] H. Fujii, S. Tsuya, R. Harada, and H. Kosukegawa, "Field test of horizontal ground heat exchangers installed using horizontal directional drilling technology," 2019.

[71] H. Fujii, H. Okubo, and K. Ahyama, “Field test of horizontal ground heat exchangers,” 2010.

[72] H. Reed, “Slimme elektrische radiator met stekker 2000w.” Retrieved on 06/05/2024 from https://shorturl.at/2M6EO.

[73] R. Outlet, “50x84,4 cm , 2000 watt ambiente elektrische paneelradiator.” Retrieved on 06/05/2024 from https://bsxl.be/radiatoren/filter/categorie-paneelradiatoren/.

[74] Bouwstation, “600x1200 t22 , 2664 watt , eco 4 gegroefde radiator.” Retrieved on 06/05/2024 from https://bsxl.be/radiatoren/filter/categorie-paneelradiatoren/.

[75] Bouwstation, “600x1800 t33 , 5728 watt , eco 4 vlakke radiator.” Retrieved on 06/05/2024 from https://radiatorkopen.be/600x1800-t33-5728-watt-eco-4-vlakke-radiator?gad_source=1&gclid=Cj0KCQjw_-GxBhC1ARIsADGgDjt8uFHIJhg_K1FRJTNhhaG8l50BvZ112xXFFOYb5ywSGxrUbaCt5d8aAhKAEALw_wcB.

[76] J. Jansen, F. Jorissen, and L. Helsen, “Optimal control of a fourth generation district heating network using an integrated non-linear model predictive controller,” *Applied Thermal Engineering*, vol. 223, p. 120030, 2023.

[77] L. Helsen, *Course on Thermal systems - Refrigerants.* 2023.

[78] Daikin, “R32, instructions for use and handling.” Retrieved from https://www.daikinchem.de/sites/default/files/pdf/Refrigerants/Daikin_R32_Handling_Brochure_EN.pdf on 24/05/2024.

[79] E. e, “Dashboard.” Retrieved from https://transparency.entsoe.eu/ on 17/03/2024, 2021.