Master's Thesis

LCA of Low-temperature District Heating Network Components

Plastic versus steel pipes, an assessment based on Kraftringen's LTDH network at Brunnshög, Lund

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Preface

This project has been done in collaboration with the energy company Kraftringen during the period September 2020 - January 2021. It marks the end of my time at Lund University and life as a student.

I would like to thank my three supervisors that supported me throughout the project. Per-Olof Johansson Kallioniemi at the department of energy sciences at LTH for your consistent help with aspects pertaining to the report and for helping me tame parts of my sometimes overambitious personality. Markus Falkvall at Kraftringen for the rapid replies to all my questions and assistance with technical information, it helped a lot. Last but certainly not least, Sara Kralmark for going beyond the expected responsibilities of a supervisor, checking in on me regularly and helping me with everything from setting me up with contacts to how the chairs work at the office. It meant a lot.

Furthermore, this project would not have been successful without the help I received from Peter Jorsal at Logstor, Denmark and Anders Jirdén at Kraftringen. I am sincerely grateful for the countless emails and phone calls that helped me give your respective areas the attention and accurate representation they deserve. I am also really thankful for the opportunity to visit the Logstor headquarters and the time spent on giving me a tour of the facility and production line.

I do apologize for the excessive use of the words "product" and "system" throughout the report. Some things you just can not get around.

Nils Olsson

Abstract

Following the development of new materials and the continuous technical progress made in the construction and energy industries, district heating as a concept finds itself on the brink of a generational shift. One of the pioneering projects leading the way is the creation of Brunnshög, an modern and sustainable district under construction in the north-eastern end of the city of Lund, Sweden. The area boasts a brand new low-temperature district heating network that is made up of both conventional steel district heating pipes but also recently developed ones where the steel has been replaced with temperature resistant plastic. Kraftringen, the energy company in charge of the network, are interested in the environmental profile of the new additions to the district heating market and how they compare to the standard pipe units. A life cycle assessment, or LCA for short, in the shape of a master's thesis is carried out to try to provide an answer.

The study examines a specific scenario and part of the district heating grid at Brunnshög where both pipe options could be installed and used. By establishing the number of pipes and additional components needed to create that particular branch of the network, the life cycles of both structures are mapped out and evaluated.

The result of the assessment is divided into four distinct categories, each representing a specific environmental issue. The plastic system, referred to as PE-RT in the report, is according to the study the slightly worse alternative in three out of four categories. The major culprit is the lower thermal insulation capacity in the studied PE-RT pipes which indirectly lead to an increased output of emissions from heat generation in power plants and similar production units. Ignoring this particular feature, the conventional steel district heating pipes are the poorer alternative in every part of the life cycle and each environmental category. The production of steel is especially hefty in the perspective of global warming. All things considered, both options perform similarly well and the small difference in the result makes for reasonable plausibility that another LCA investigating the same topic would yield a set of different conclusions.

The report also aims to act as a comprehensible introduction to the field of life cycle assessment, providing an extensive theory chapter and a general report structure emphasizing accessibility.

This master's thesis concerns a case study and any result provided is first and foremost applicable to the investigated scenario. Any attempt to apply the findings on other similar contexts or the district heating industry in general should be done cautiously and only if there is an sufficient resemblance to the presented scenario.

Contents

Nomenclature

* The definition is cited from the SS-EN ISO 14040 (2006) series standard [1], [2].

** Stricter definitions may exist.

Abbreviations

ALCA	Attributional Life Cycle Assessment
AP	Acidification Potential
CH_4	Methane
CHP	Combined Heat and Power
CLCA	Consequential Life Cycle Assessment
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DH	District Heating
EP	Eutrophication Potential
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDPE	High-density Polyethylene
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LTDH	Low-temperature District Heating
NH_3	Ammonia
NMVOC	Non-methane Volatile Organic Compound
N_2O	Nitrous Oxide
NO_x	Nitric Oxide NO & Nitrogen Dioxide NO_2 et al.
ODP	Ozone Depletion Potential

PM	Particulate Matter
POCP	Photo-Chemical Ozone Creation Potential
PE	Polyethylene $(C_2H_4)_n$
PE-RT	Polyethylene of Raised Temperature
PUR	Polyurethane
SO_x	Sulfur Oxides

Terminology

abiotic	devoid of living organisms or not of biological origin
**activity	an operation that takes inputs in the form of material and energy, transforming it into one or more outputs
*allocation	partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems
characterisation	the second step of the environmental impact assessment. The inventory data's impact on relevant environmental effect categories is calculated through the use of a characterisation coefficient
*characterisation factor	factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator
classification	the first step of the environmental impact assessment with the objective to connect data categories with environmental effect categories
cradle to gate	part of life cycle that concerns the phases raw-material extraction, refinement and manufacturing
cradle to grave	part of life cycle that concerns the entire life cycle of a product
*cut-off criteria	specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study

data category	a flow of material, energy or other measurable unit found within the studied system, for example: iron [kg], heat [MJ] and paved ground [m^2]
*data quality	characteristics of data that relate to their ability to satisfy stated requirements
diffuse emissions	emissions who's origins are unknown or unworthy of detailed scrutiny but who's accumulated effect can not be neglected
elementary flow	flow of energy or material entering or leaving the system previously or later unaltered by direct human activities
emission	Substance, usually on a molecular level, produced and released to the environment through the course of or after a process
*environmental impact category	class representing environmental issues of concern to which life cycle inventory analysis results may be assigned
environmental impact assessment	one of the main parts of an LCA procedure which aims to present the environmental impact of the inventory data
*functional unit	quantified performance of a product system for use as a reference unit
gate to grave	part of life cycle that usually concerns the production phase of a life cycle
*input	product, material or energy flow that enters a unit process
inventory	the second step of an LCA consisting of data collection and system and process descriptions
*life cycle	consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal
*life cycle assessment, LCA	compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle
*life cycle inventory analysis, LCI	phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle
*life cycle impact assessment, LCIA	phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product
life cycle phase	one distinct chapter in the life of a product, e.g. manufacturing

meta data	data about data; descriptive information regarding a piece of data
normalisation	inventory data expressed as amount per unit reference flow or reference value
*output	product, material or energy flow that leaves a unit process
**process	see "activity"
process tree	a graphical illustration of a product system
*product system	collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product
radiative efficiency	relative effectiveness of a greenhouse gas to restrict long-wave radiation to escape the atmosphere
*reference flow	measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit
*releases	emissions to air and discharges to water and soil
secondary data	data provided by an LCI database
*sensitivity analysis	systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study
*system boundary	set of criteria specifying which unit processes are part of a product system
*uncertainty analysis	systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability
*unit process	the smallest element considered in an LCIA for which input and output data are quantified
virgin material	material sourced directly from nature
weighting	third and optional step of the environmental impact assessment which aims to rate a system's total environmental impact using one single score

1 Introduction

As the world continuously strive for modern measures to improve energy utilisation efficiency and to minimize the environmental footprint related to energy production, fuels are often the main focal point of the general discussion. District heating, a vital cornerstone in the Swedish energy ecosystem, is no exception. Alone providing approximately 14 percent of Sweden's total energy consumption [3] [4], small changes to the concept as a whole may have a significant impact. However, district heating as a system in the context of environmental issues, is more than the sum of its fuels. Distributing the produced heat requires a network of pipes, substations and additional components, all accompanied by their own environmentally burdened life cycles.

Currently, the initial stages of a migration towards the 4th generation of district heating are under way. An important characteristic of the fourth generation will be to lower the network temperatures as a way to, among other things, reduce the heat losses in the system. As a result, materials and products that previously were unfit for the application due to various reasons, are now emerging as viable options to be incorporated in district heating networks. One such possibility is to switch the inner so called carrier pipe in a district heating pipe, which transports the district heating water, from a conventional steel version to one made out of temperature resistant plastic. This has not been feasible during the current generation since the operational temperatures and pressure levels are outside the range of what these plastic material can support.

Kraftringen, an energy company active in Lund, Sweden and some neighboring municipalities, has already to a large extent implemented this new technology in their upcoming low-temperature district heating network (LTDH) at Brunnshög. Brunnshög is an emerging and state of the art district in the north-eastern end of the city of Lund. The pipes intended for use have carrier pipes made out of polyethylene of raised temperature (PE-RT) and the entire product is flexible and can bend around corners. The expectation is that, by the use of this setup, installations times and costs, transport costs and negative environmental effects can be reduced. The latter refers to a preconceived notion within the district heating industry that steel, and by extension steel DH pipes, are accompanied by a highly emission-burdened manufacturing process. There is merit to that claim since the ferrous and non-ferrous metal industry is among the most carbon-intensive in the world [5]. Yet, the total environmental impact of a product system extends beyond those of the production processes. Kraftringen is interested in gaining further insight into the environmental facets of different pipe materials. This master's thesis aims to provide that information by carrying out a life cycle assessment (LCA), comparing the conventional steel DH pipes with the new plastic counterparts.

1.1 Purpose

This master's thesis aims to evaluate and compare, on a case basis, the performance of two different district heating pipe systems and the aggregated impacts from their respective life cycles. The considered case is limited to the isolated LTDH network at Brunnshög in Lund, Sweden. The report strives to produce general conclusions applicable to the entire industry but it goes without saying that any acquired result first and foremost represents the specific situation at Brunnshög.

Besides the covered topic, the report strives to be lucid and accessible to anyone no matter their previous experience of LCA methodology or the technical aspects of district heating infrastructure. Great emphasis has been put on the structure of the layout. Some elements that might be omitted in standard LCA reports, such as detailed descriptions of LCIA categories and certain manufacturing processes, have purposely been included to make the report as comprehensible as possible.

The objective of the report is to answer the following questions:

- How does a plastic (PE-RT) district heating pipe system compare to its steel counterpart in a life cycle assessment perspective?
- Which are the hotspots related to the two product systems?
- How do changes to certain parameters in the model alter the outcome, e.g. the origin of a certain component?

Regarding the first question, there are several ways the life cycle of a product can impact the environment. to facilitate the comparison, many different categories, each representing one particular phenomena, exist. The ones studied in this report are further described in section 3.4.

A "hotspot" in LCA terms implies an activity or process that constitutes a considerable portion of a systems total environmental impact. Even though sometimes easily pinpointed in advance, it is important to search for and localise hotspots in every part of a product's life cycle. They play a significant role since they act as beacons to where further research should be focused and because they might highlight the importance of neglected areas.

As for the matter of key parameters, the general approach in this study is to find the areas with a large environmental impact where the product systems can be adjusted or represented in an alternative way. Which areas or phases of the life cycle are of interest can only be assumed at the beginning of the project and they will ultimately be decided after a clear idea of the system has been obtained. The chosen areas are presented in the *Parameter Analysis*, section 8.

1.2 Previous Studies

The district heating pipe industry is rather small and does not occupy the attention of the public, as could be argued for most infrastructure components. The amount of studies conducted on the topic can be assumed proportional to the external demand for scrutiny by the public. With that said, some articles written specifically on the subject are available, the most notable (and the ones listed below) from a team of researchers at Chalmers University of Technology.

- Life Cycle Assessment of District Heat Distribution System
  - *Part 1: Pipe Production* [6]
  - *Part 2: Network Construction* [7]
  - *Part 3: Use Phase and Overall Discussion* [8]
- *Miljöbelastning från Läggning av Fjärrvärmerör* [9]

These reports do not cover every aspect of the DH pipe life cycle but instead focus on thoroughly describing particular phases of said life cycle. Depending on the chosen system boundaries (see section 5.2) other articles could be included on the list above. Yet, as they do not in the same way stick to the core subject, they are not mentioned.

1.3 Limitations

The three main limitations characterising this master's thesis are the classic three present in many LCAs, i.e. expertise, time and resources. Neither the author, nor the representatives from the main involved parties have a background in LCA practice or theory but do possess great knowledge in their respective fields of expertise. Part of the project that an experienced LCA practitioner could have spent on research thus had to be dedicated to the study of general LCA methodology. Leading in to the concept of time, a twenty week-long project timeline is, as it stands, a sufficient period to achieve concrete results. However, as with each one of the three parameters, a proportionality to the accuracy of the end result exists. The most noticeable limitation to the project is the choice of software and database which in this case is restricted to non-commercial and open-source versions.(further explained and discussed in section 4 and 9).

1.4 Structure of Report and Additional Advice to Readers

This report combines the structural elements of a master's thesis and LCA study. To avoid confusion, some remarks can be made. Normally, when reading a master's thesis one would be used to seeing the following structure: *Introduction - Background - Theory - Method - Results - Analysis - Conclusions*. A conventional life cycle assessment on the other hand requires three specific chapters: *Goal and Scope - Inventory - Life Cycle Impact Assessment*. Their meaning and purpose are described in section 3. The *Goal and Scope* can not explicitly be found as a chapter in this report but it is represented by the subsection *Purpose* 1.1 together with section 5 *Case Description*. The *Inventory* would in a more traditional master's thesis most likely be part of the *Method*. *Life Cycle Impact Assessment* correspond to the results of the study.

Some words appear often and in varying contexts. The following clarifications are made:

- **System** - The word *system* usually refers to the collection of components that make up the studied PE-RT or steel DH branches. However, due to the word's versatility, any group of connected objects, ideas or actions could also be described as a system.
- **process, activity, procedure** - These words are used more or less in an interchangeable manner. They all aim to describe either an action or something that is happening which take inputs (material, energy etc.) and turn them into outputs.
- **emissions, releases, outputs** - With some exceptions in the case of the word output, in this report these words refer to compounds being released to the air which have an impact on environmental systems.

2 Background

2.1 District Heating and LTDH - *Low Temperature District Heating*

District heating is an all-around and singular solution to the problem of heating buildings in urban areas. The concept involves one or a couple of central production units, e.g. a combined heat and power (CHP) plant, which generates heat and transfers it to water in an enclosed grid. The hot water is then pumped from the heat production unit to the customers connected to the DH network where, through heat exchangers, the energy is transferred to the buildings. The cooled DH water returns back to the plant and the cycle repeats. The method lends itself particularly well to areas with a rather high population density. Initially the idea was concretized as a way to improve the air quality in cities by replacing the combustion in individual residences with one or a few main units and relocating the operation to the outskirts of town [10]. Given its structure, the potential to improve and modernize the system in a coordinated fashion is significantly higher than in the case of the preceding situation with separate and individual production units. For that reason, the technology will play an important role in the current and future challenges facing society and the planet. Even though district heating customers are, in comparison to the electricity market, subject to a monopoly, there is still a competition imposed by alternative technologies such as heat pumps and natural gas. There is thus a parallel incentive for energy companies to improve and modernize DH networks and techniques besides the obvious environmental benefits.

District heating can in a techno-historic perspective be divided into four categories or generations. The first one was characterized by its heat carrying medium which at the time was steam. It remained relevant up until the 1930s where the second generation arose and a shift from steam to pressurised water was introduced on the market. The components were large and material-intensive, for example the pipes were often enclosed in a concrete culvert. Beginning in the 1970s and becoming dominant in the 1980s, the 3d and current generation initiated a move towards lower supply temperatures and improved components such as the prefabricated pipes with polyurethane based insulation. Now the industry finds itself on the brink of a fourth generation. Coined at an IEA-seminar in Reykjavik, Iceland in 2008 [11], the term fourth generation district heating (4GDH) does not have a strict definition but a couple of key ambitions and directions are proposed:

- Reduce the supply temperature further, down towards temperatures around 50 °C and below.
- Improve the insulation of buildings connected to the grid.
- Increase the synergy between the network and the buildings by implementing measurement devices and intelligent control (all the way down on an apartment level) which will more accurately predict or portray the heat requirements.
- Work to increase the share of intermittent energy sources, e.g. heat from solar power, and waste heat as input to the network.
- Improve the network system components, especially in regards to thermal insulation.

There are more aspects and suggested ideas connected to the vision of the next era of district heating but the ones mentioned above are among the most important. Low-temperature district heating (LTDH) is a term that has become somewhat synonymous with 4GDH. As the name suggests, the focus is on the temperature of the district heating water. However, it is difficult to achieve a successful implementation of an LTDH grid without addressing the other aspects of the 4th generation such as improved heat conservation in buildings.

The information in this subsection is based on [12].

2.2 District Heating at Brunnshög

Brunnshög is a district under construction in north-eastern end of Lund. The project is still in an early stage and the district will continue to be molded and grow during several decades. Since it is a completely new area and not really an extension of an already existing one, there is and has been an opportunity to build and plan with a singular vision emphasizing modern and sustainable infrastructure and energy solutions. It is also built in conjunction with two large research facilities, MAX IV and the European Spallation Source (ESS). Their presence will help attract national and international researchers and give the district a scientific profile. Due to the size of and the operations carried out at the two facilities, the energy demand is of equal proportions.

As a convenient result, a large amount of waste heat is created and used as the primary input to Brunnshög's low-temperature district heating (LTDH) network. It is estimated that the area will have an annual need of 23 GWh of low temperature heat, something MAX IV and ESS will comfortably be able to provide with their respective annual output of 28 and 100 GWh of low temperature waste heat. ESS will also produce 100 GWh of high temperature waste heat that could be connected to the municipality's main conventional grid. The LTDH network at Brunnshög will operate at 10 bar and a supply temperature around 65 °C.

Since the district is still being constructed it is uncertain how many final customers there will be connected to the grid but an upper estimate suggests a figure of 40 000 people. The LTDH network in Brunnshög is not hydraulically connected to the main DH network in Lund as they operate on different pressure and temperature levels. However they can interact through heat exchangers, making it possible for the isolated grid at Brunnshög to receive backup in the case of paused operations at MAX IV and ESS. There are additional circumstances making this layout feasible. First and foremost, the buildings at Brunnshög are brand new with high energy efficiencies and great thermal insulating capacities. Their heat requirement is therefore lower than most contemporary housings and can be furnished with lower temperature heat. Secondly, the fact that both research facilities are located within the area minimizes the inevitable heat losses that occur throughout the system. Besides the traditional use for district heating in buildings and given the surplus of available excess heat, new applications will be tested such as heated tram stops.

2.3 Major Involved Parties and COOL DH

The LTDH network at Brunnshög is a project involving multiple stakeholders and active parties. The ones pertinent to this master's thesis all have a direct tie to the development, progression and evaluation of the network, specifically the DH pipes and related components comprising the infrastructure.

- **Kraftringen** is an energy company owned by the municipalities Lund, Lomma, Eslöv and Hörby. They own and operate the local energy infrastructure and provide services in electricity, heat, cooling, gas and fiber to name a few. At Brunnshög they act as proprietor of the network and are responsible for the generation and distribution of heat as well as the maintenance of the components. Kraftringen is the party having requested this particular master's thesis.

- **Logstor** specializes in the development and production of pipe system components for district heating, district cooling, oil, gas and other industry applications. Present on an international level, their enterprise is spread over Europe with the headquarters and main production facility situated in Løgstør, Denmark. In the project at Brunnshög, Logstor manufactures and provides the pipe units and the other additional network components. This is true for both the plastic and conventional steel pipes. They are also the provider of one type of software, *Logstor Calculator*, used in this study.
- **NCC** is one of the largest construction companies on the Nordic market. They engage in most types of infrastructure and building projects. NCC is responsible for the large parts of the installation process at Brunnshög, i.e. excavation of DH pipe trenches, laying of pipes and trench restoration.
- The faculty of engineering at Lund University, commonly referred to as LTH, contributes by assessing and evaluating the performance of the pipes, related components and the LTDH network as a whole.

A major reason why Brunnshög has become the testing ground for up-and-coming district heating technology is the joint research project COOL DH. The project aims to help municipalities and cities plan and build new and efficient district heating systems as well as to improve and modernize existing DH infrastructure. COOL DH is in turn a recipient of funds from the large scale EU research and innovation program *Horizon 2020*, established as an instrument to secure Europe's future competitiveness. COOL DH is a shell made up of a mix of private companies, public institutions and trade associations, among which the ones mentioned above (except NCC) are involved. The project concerns two specific real life cases, the one at Brunnshög in Lund and the other in the municipality of Høje Taastrup in Denmark. In practical terms, COOL DH's goals consist of:

- Develop and build cooling and heat recovery process systems which permit heat recoveries to LTDH grids.
- Design and produce an LTDH grid using non-conventional pipe materials.
- Innovate and design adequate heating systems and controls inside buildings, combining LTDH with distributed integration of renewable and locally produced heat.
- Conceive solutions to the creation of viable business and pricing models as well as ensuring good (low) return temperatures, and at the same time providing construction companies with maximum flexibility regarding the choice of heating systems.
- Demonstrate a complete and functional system with all required components suitable for low DH temperatures (40–65 °C). This includes the display of systems for domestic hot water heating without the risk of legionella.

The information about companies and institutions are gathered from either their own publicly available material (websites, slideshows etc.) or internal communications.

3 Theory - *Life Cycle Assessment*

This section describes the fundamental aspects of the life cycle assessment methodology. It is mainly based on the contents of the the book "*Livscykelanalys - En metod för miljöbedömning av produkter och tjänster*" [13] and the two SS-EN ISO Standards 14040 and 14044, where the 14040 describes LCA in a general way and the 14044 details the requirements for conducting an LCA. If not mentioned explicitly, information (including tabulated data) stems from these sources. The proposed method explained in this section may not fully resemble the one used in the main report and should be viewed primarily as an introduction to the subject.

The Life Cycle Assessment, commonly known through its abbreviation LCA, is a method to assess the total environmental impact of a product or service. It is defined by the the SS-EN ISO 14040 (2006) standard as:

> *"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system through its life cycle."* [1]

It functions as a framework and/or tool used to address environmentally oriented questions regarding products and services and to act as a foundation for decision-making processes.

As illustrated by figure 1, the method can be divided into four phases:

1. **Goal and Scope:** Deciding the objective of the study, the purpose of the study, what system is to be studied and what to include in and exclude from the study.

2. **Inventory:** Describing the examined system, its processes and flows. Calculating and assembling the data pertaining to the system and its components.

3. **Impact Assessment:** Through the data and information gathered in the inventory phase, analysing the environmental impact of the system using a certain impact assessment method.

4. **Interpretation:** The act of continuously tweaking and updating one's approach and project layout as a response to gained knowledge about the examined system.

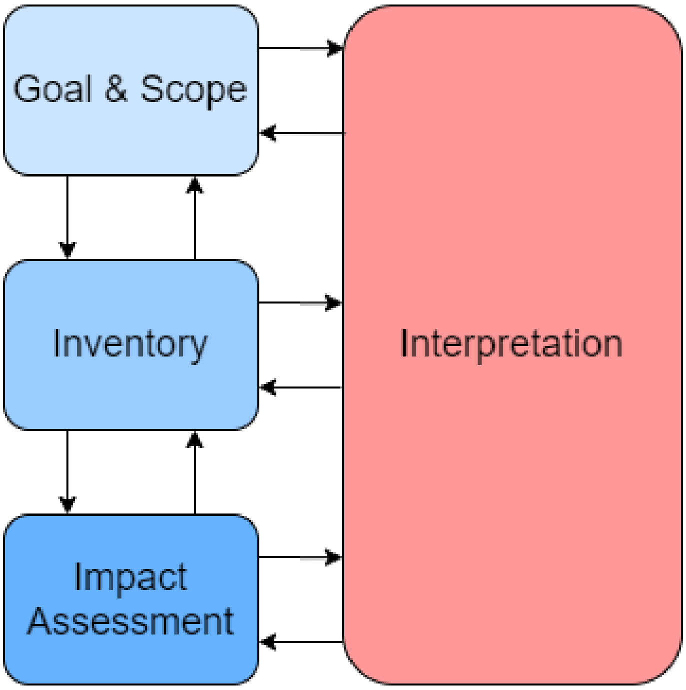

Figure 1: An illustration of the LCA Process.

3.1 Goal and Scope

The initial phase of the LCA lays the groundwork for the assessment by describing its purpose, objective and scope. By establishing a firm foundation, one facilitates the remaining procedure and reduces the risk of straying to far from the matter at hand.

If the purpose of the project is to compare two or more product systems, a common denominator needs to be established in order to create a fair and coherent comparison. In the LCA field this denominator is dubbed *functional unit*. Its purpose is to allow for the comparison of several different solutions to the same problem, even though they might be inherently different from one another. The functional unit is usually defined as a broadly specified need that can be fulfilled or achieved through the implementation and usage of a certain product. An example of a functional unit could be: *"Displacement of 10 kg object the distance of 1 km"* or *"foot ware intended for mountainous terrain"*. These two examples illustrate the versatility of the LCA method. Depending on the objective, resources and scale of the LCA, the functional unit can purposely be made vague or specific in order to fit the given scenario. The first example could be solved using anything from a wheelbarrow to a helicopter, consequently requiring a more extensive inquiry. On the other hand, the second example is really narrow in its description. While automatically limiting the amount of possible solutions suitable to fulfill the functional unit, the process becomes less strenuous. In other words, the functional unit should be chosen with care in order to most adequately represent the system but at the same time to avoid unnecessary work or to neglect possible product options.

The scope of an LCA is proportional to the boundaries set for the assessment. Just as it is important to put effort into defining the functional unit in an adequate way, the system boundaries are of equal importance. Striving for accuracy, the ideal case would be to include every possible aspect, detail and piece of data available in the assessment. This is however unrealistic as resources, time and expertise are limiting factors. Furthermore, a less meticulous study might yield similar and equally satisfying results leading to the same decision making as the ideal case would have generated. Echoing this reasoning, The Pareto principle, which is applicable in many fields of science, states that 20 percent of the parameters are responsible for 80 percent of the outcome [14].

According to the referenced book [13], the following categories need to be considered when determining the system boundaries.

- **Environmental Systems:** A product or service will throughout its lifetime interact with several external domains, be it through the exchange of material, energy or information. Consider a shoe with a rubber sole as the studied system. The origin of the material and energy going into making the shoe, in other words flow of material and energy into the system, is certainly of interest in an LCA but is the exchange of rubber/material leaving the sole and going into nature following years of use and structural degradation of equal importance?
- **Components, Subsystems and Services:** Usually a product system is constituted by several subsystems which in turn are also made up of additional subsystems and so on. Components within the system may be third party products with complex and undisclosed productions chains. Furthermore, the impact from associated services/activities related to the existence of the system such as transportation of goods and/or computational power may or may not be relevant for an LCA. Common practice is to include activities with a clear and direct tie to the system.
- **Geography:** The impact of a system may vary depending on its geographical location throughout its lifetime. A plastic bucket produced and used in Sweden might have vastly different impact on its surroundings compared to one in China. Pollution can, depending on meteorological patterns or water flow, spread in different ways depending on the location. Thus, concerning geographical boundaries, one has to decide what a reasonable area or distance from the system should be for a given scenario.
- **Time:** Even though an LCA strives to measure the effects of system during its entire life, it can sometimes be challenging to draw distinct lines as to where it begins, ends and where transitions from one phase to another occur. An old car at the junkyard might have outlived its purpose and might be considered the final state of that system. However it still actively interacts with its surroundings through physical degradation. Moreover, some effects produced by a system during its life might only become apparent/active long after the system is gone.

Not every point above might be relevant for each and every LCA but they provide simple yet effective guidelines as to how approach the process of system boundary selection. Other aspects that could be considered include if the product is passive or active and if the technology behind the product has reached "technological maturity" or not.

3.2 Inventory

The Inventory step revolves around describing the different product systems, their function, characteristics and life cycles. Furthermore, the input and outputs of the different life cycle phases should be listed. This data and information is referred to as *Life Cycle Inventory* data or LCI for short.

When having defined the functional unit, one can proceed to list and explain the considered products or solutions. One way to do this is to specify the various components constituting the products by listing their purpose, material composition, weight etc. Characteristics relevant for the study at hand should be prioritized.

The life cycle of a product can, depending on the project scope and selected system boundaries, be quite extensive and complex. It is helpful to create a visual description of the system, for example in the form of a flow chart. This can be done in several ways and on several levels. For complex systems with several levels or layers of processes, multiple process trees can be established as a way to further clarify the situation for oneself and the targeted audience. The goal is to gain a holistic view of the studied life cycle.

Figure 2 is a visual representation of a fictional life cycle of a bed.

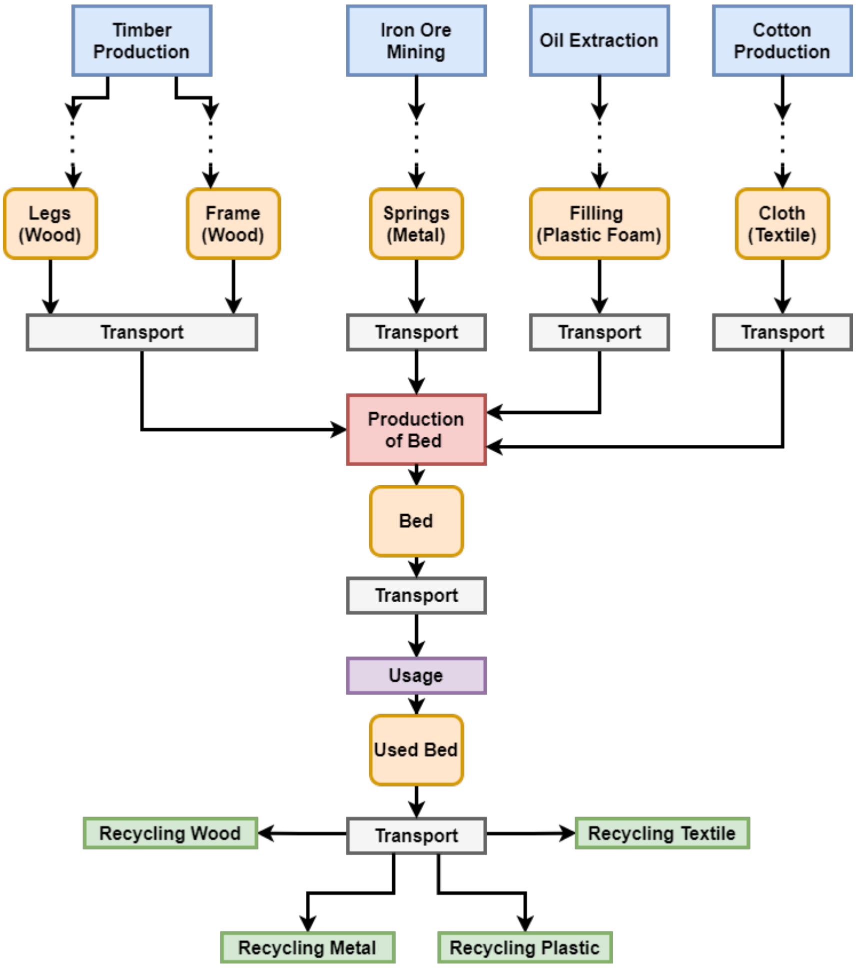

Figure 2: Example of a life cycle presented in the shape of a flow chart.

With a clear understanding of the layout of the life cycle, one can start to collect data about the processes. This is usually the most time consuming part of an LCA. Valuable data are for example what materials flow through the system, their respective weights, duration of processes and energy usage. Knowing to what extent the data collection should be carried out is key to a successful investigation. Data is not always available in the same shape, quality or quantity from one case to another. It is therefor important to try to consult several different parties and sources. Different pieces of data may also require different means of acquisition.

Suggested by the main book used as reference material [13], one can assemble the collected data in a table and assort them in broad categories. An example of this is displayed in table 2.

Table 2: Classification of different types of data of a fictional process. The normalized data is based on the production of 160 kg/year of product(s).

	Data Category	**Inventory Data**	**Normalized Data**
Resource Usage	Polystyrene [kg]	100 [kg/year]	625 [g/(kg product)]
	iron [kg]	50 [kg/year]	313 [g/(kg product)]
Energy Usage	Electrical Energy [MJ]	60 000 [MJ/year]	375 [MJ/(kg product)]
	Heat [MJ]	20 000 [MJ/year]	125 [MJ/(kg product)]
Emissions to Air	Carbon Dioxide [kg]	800 [kg/year]	5 [kg/(kg product)]

If data is missing for a certain category it should not automatically be set to zero or assumed non-existent. Instead, it can be evaluated based on reasonable assumptions or data from similar processes. If ultimately deemed insignificant to the analysis, the value can be set to zero.

The importance of adhering to geographical and timely boundaries etc translates well to the requirements put on the data collected in the LCA. SS-EN ISO 14044 (2006) lists 10 points necessary to consider when collecting data among which geography, time, statistical accuracy and reproducibility are aspects.

Furthermore, every piece of data collected for the assessment should be accompanied by information characterizing said data. This supplementary information goes by the name of meta data. It details things such as measurement tools, number and duration of tests, geographical position and anything else pertinent and related to the retrieved data.

3.3 LCIA - *Life Cycle Impact Assessment*

Having assembled a large amount of data during the inventory phase, what remains is to try to establish the relationship between the LCI data and its effect on the environment.

Although globally recognized as harmful to the environment, man made emissions on a molecular level can still be, for the uninitiated, difficult to link to real life consequences and different types of environmental deterioration. Would everyone really be able to say exactly how and why a surplus of NO_x affects nature?

For this reason each type of emission present in the system is related to one or more categories such as eutrophication, climate change and deterioration of the ozone layer. Which emission that correlates to which category are based on natural scientific cause and effect relations. This procedure is known as *Classification*.

The second step, known as *Characterisation*, aims to multiply the emission value [g/(kg functional unit)] with a unique factor assigning a value/rating to a data category within the context of one of the categories mentioned in the subsequent section. The characterisation factors function by assigning one type of emission as a reference. A well known example is the so called carbon dioxide equivalent factor used to compare the global warming potential of a substance/molecule to the one of carbon dioxide which is set to 1 as a reference value. The factors presented in table 3 are only meant as an example and the ones used in the actual study are instead presented in table 24.

Table 3: Tabulation displaying different data categories' impact on phenomena such as global warming and nitrification through adaptation by characterisation factors (source: CML (non baseline) v4.4). If not applicable, value is denoted by "-".

Data Category	CO_2	NO_x
Inventory Data [kg/functional unit]	12	1.6
Characterization Factor: kg $CO_{2,eq}$/(kg emission)	1	5
Result [a]GWP	12	8
Characterization Factor: kg $NO_{x,eq}$/(kg emission)	-	1.2
Result [b]EP	-	1.9

[a] *GWP = Global Warming Potential (CO_2 equivalents)*
[b] *EP = eutrophication potential (NO_x equivalents)*

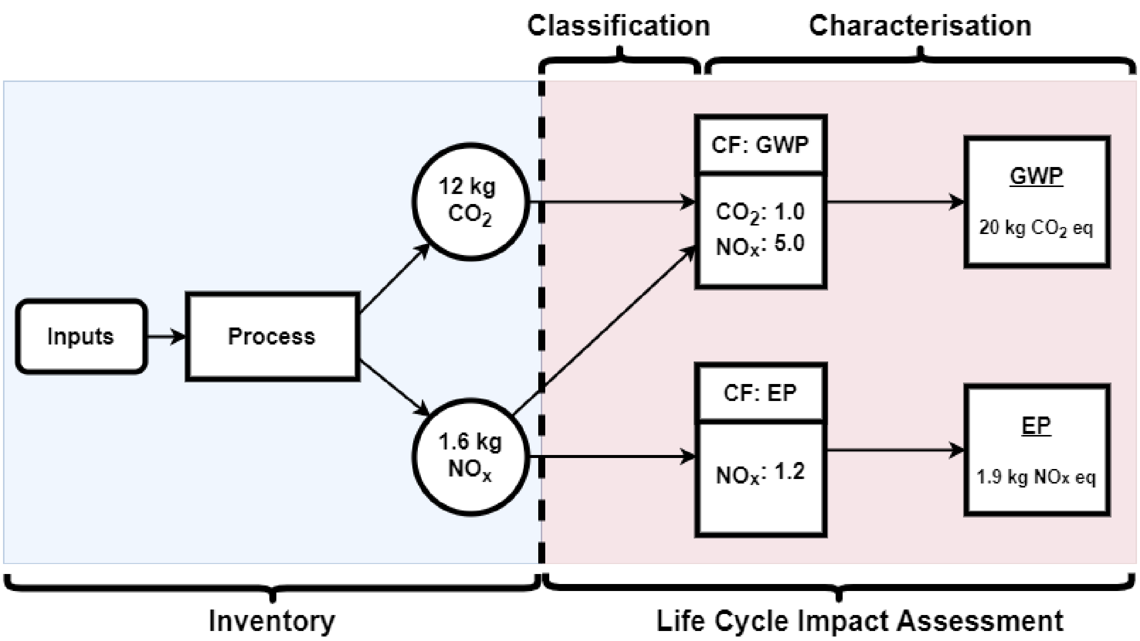

Figure 3: A simplified version of the Inventory and LCIA steps concerning a fictional process.

Finally, there is also an optional and somewhat controversial step called *Weighting* that can be included in the LCIA. It is not included in the main report and therefore not further explained here.

3.4 Environmental Impact Categories

The end goal of an LCA is to produce an overview of a product's or system's impact on the environment and, depending on the study, human health. There are of course more than one way to affect systems of this magnitude and complexity. In the LCA domain, such a "way" is called *environmental impact category*. There are several different categories and the ones considered in this report are listed and explained below. As mentioned in the previous section, to be able to quantify the aggregated effect of molecules, compounds etc., each category uses a reference unit which in many cases is represented by a specific molecule. It is also worth noting that one type of substance can have an impact in more than one category.

This subsection (section 3.4) is mainly based on the document *Product Environmental Footprint (PEF) Guide* [15] produced by the European Commission and the book *Energy Sustainability* [16] by authors I. Dincer and A. Abu-Rayash.

3.4.1 AP - *Acidification Potential*

Acidification is directly linked to concentration of hydrogen anions H^+ in soil and bodies of water on land. Acidification occurs naturally in the environment keeping well established ecosystem in balance. Compounds such as sulfur oxides (SO_x), ammonia (NH_3) and nitrogen oxides (NO_x) are, after being released into the air, dispersed into nature through acid rain. while there, the substances react in different ways with the surroundings, generally releasing H^+ anions which in turn lower the local PH value (more acidic). The reference unit *Sulfur Dioxide Equivalent* - SO_2, eq in moles is usually adapted.

The tangible results of acidification are disturbed ecosystems and death of biological organisms.

The discussed type of acidification should not be confused with oceanic acidification which is mostly a consequence of increased emissions of carbon dioxide [17].

3.4.2 EP - *Eutrophication Potential*

Eutrophication potential refers to the damages to ecosystems caused by the anthropogenic addition of nutrient compounds, e.g. nitrogen and phosphorus. Usually in a limited supply, a surplus of these nutrients create favorable conditions for algae and underwater vegetation which as a result increase greatly in numbers. When dead and decomposing, these plants are devoured by aerobic bacteria on the bottom of the body of water which simultaneously consumes large amount of oxygen, effectively killing other oxygen-dependent species in the ecosystem. This can be divided into the subcategories terrestrial, freshwater and marine. In this report the latter one is considered.

The reference unit is commonly *Phosphate Equivalent* - PO_4, eq in kilograms but nitrogen oxide equivalents are sometimes deployed.

A major culprit among human activities leading to increased eutrophication is the usage of fertilizers in agriculture.

3.4.3 GWP - *Global Warming Potential*

The atmosphere's ability to store heat from incoming solar radiation is dictated by its molecular composition. Some molecules found in or released to the atmosphere have a significant impact on the radiative forcing, i.e. the difference in thermal radiation absorbed by the earth and thermal radiation discharged into space [18]. The reference molecule for the GWP category is carbon dioxide (CO_2) and thus the reference unit *carbon dioxide equivalent* ($CO_{2,eq}$) in kilograms.

An important notion is the time dependency of substances in a GWP context. A molecule's capacity to contain heat in the atmosphere changes over time. As a result, different time frames, usually 20, 100 and 500 years (GWP20, GWP100 and GWP500), are studied separately, all starting from the introduction of the substance to the atmosphere. GWP100 is the chosen frame of reference in this report.

Direct and visible effects linked to this phenomena included melting ice caps, elevated storm and flooding frequency as well as increased ocean acidification.

3.4.4 POCP - *Photochemical Ozone Creation Potential*

Photochemical ozone is more commonly know by the name photchemical smog and is, together with sulfurous smog, what is usually simply denoted as smog. Unlike ozone in the ozone layer, photochemical smog is a hazardous and created when man-made emissions, most notably VOCs (volatile organic compounds) and nitrogen oxides, react with sunlight at ground level. The POCP is dependent on many parameters including time of year, geography and the level of urbanisation.

More than one reference unit exist but nitrogen dioxide or monoxide equivalents as well as NMVOC equivalents in kilograms are common.

3.4.5 ODP - *Ozone Depletion Potential*

The ozone layer, situated in the bottom of the earth's stratosphere, blocks UV radiation from reaching the planet's surface. UV rays are harmful to humans and animals, increasing the risk of for example skin cancer. Certain compounds such as CFCs, HFCs and Halons are the driving force of ozone depletion. When reaching the ozone layer, they are split by the UV radiation triggering a chain reaction which ultimately leads to diminishing of ozone molecules (O_3) in the ozone layer, subsequently allowing more UV light to reach the surface.

The reference unit is *CFC equivalent* - CFC_{eq} in kilograms.

3.4.6 Additional Environmental Impact Categories

The LCA methodology provides a lot of flexibility regarding the choice of studied parameter or area of interest. It is not in any way a requirement that a certain molecule act as the reference unit. Some categories highlight the usage of primary energy sources (coal, wind, oil etc.) measured in megajoules and others simply look at the depletion of abiotic resources in kilograms. Furthermore, water use in cubic meters, ecotoxicity, land use, to name a few, are also part of the LCA domain.

3.5 Allocation

To allocate, in an LCA context, implies deciding how to distribute the environmental impact of a system or process over its associated flows.

A standard example is a manufacturing line where two products A and B are created. Based on what is considered relevant for the studied activity, some type of common and measurable reference unit should be used as basis for the allocation. Typical units are weight, volume, market value etc. Suppose that product A weighs 3 times that of product B but product B has a 9 times higher market value than A. Given these conditions, the result of the allocation would be 75 percent for A and 25 percent for B if weight was the reference factor. If instead market value was chosen, the distribution would be 10 percent for A and 90 percent for B.

Another common example of an allocation problem is the likely scenario where an output from one life cycle becomes an input to another life cycle. If waste, generated from life cycle L1, could be used as fuel in a process that is part of life cycle L2, then the question remains as to which life cycle the emissions related to combustion and processing of the fuel should be allocated. A way to circumvent this altogether is through system expansion. This implies changing the purpose of the study or the system boundaries in order to include an entire process that was previously subject to an allocation procedure.

3.6 LCA in Practice

Carrying out an LCA undoubtedly implies a lot of research, contact with relevant parties and calculations. Besides this there are three types of resources used almost universally in the LCA domain. They are: LCA dedicated software, databases and impact assessment methods.

LCA software serve as a central platform for modeling the studied system. They allow for different types of calculations and simulations and they provide a convenient interface for accessing databases and impact assessment methods. Commonly used computer programs on the market are Simapro [19], GaBi [20] and OpenLCA [21], where the latter is open-source and free to use.

However, the software are only as good as the datasets available on the platform. The databases contain large amounts of professionally collected and evaluated process data from a large array of different areas such as resource extraction, refinement, production, usage and recycling. Data provided through these channels are usually know as *secondary data*, recognizing its role as back-up to the information collected firsthand by the LCA practitioner. Databases are usually not connected to the software developers and are instead created by separate organisations. Arguably the most well-known is Ecoinvent [22]. Others include Exiobase [23] and Agribalyse.

A common denominator for most software and databases is the price tag. Even though the cost varies between products and companies, the intended customers are usually corporations or universities capable of covering the licensing fees.

The way to approach environmental impact assessments is not definitive and to this day the subject of debate. Different frameworks, so called *impact assessment methods*, have been developed independently with various mindsets and priorities. Their collective function is to provide a basis of evaluation in the form of impact factors and commonly also weighting indices. In simpler terms, they dictate, among other things, which impact categories (GWP, AP, EP etc.) to consider, their relative importance to one another and how "potent" a substance is in regard to a certain impact category. As a result, there is no need to actually perform the *classification* and *characterisations* steps, the method got it covered. Popular options are Ecoscarcity, Ecoindicator 99, CML and ReCiPe. Broadly speaking, there are two types of methods, so called *midpoint* and *endpoint* methods. The difference between the two is that the former only goes as far as explaining the outcome somewhere in the middle of a series of subsequent consequences while the latter focuses on the end result. As an example, consider a cause and effect chain, describing the phenomena eutrophication and beginning with the release of nutrients. The midpoint methods would then perhaps describe the increasing concentration of substances in a lake while the endpoint methods would center around the extinction of fish in the lake. The strength of the midpoint approach is the clearer connection between cause and effect (the effect being the midpoint in this case) while the endpoint approach has the advantage of being more accessible and easier to convey [24]. The selection procedure for choosing an impact assessment method is described in the SS-EN ISO 14044 (2006) standard.

Finally, there are two types of LCA studies that can be carried out, *Attributional Life Cycle Assessment* (ALCA) and *Consequential Life Cycle Assessment*. The exact definitions are rather complicated and not explained in further detail here. This report is an ALCA and this distinction is included due to the recurrence of the abbreviation ALCA throughout the report.

Figure 4 summarises the three types of LCA related resources discussed above.

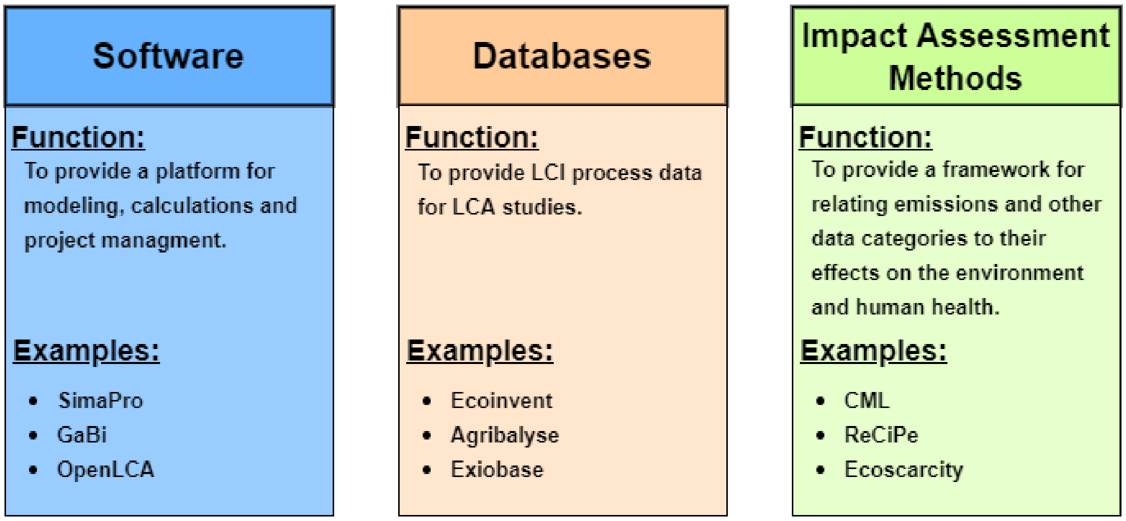

Figure 4: Different types of resources used when conducting an LCA study.

4 Method and Data Quality

The three questions posed in the research questions all require an LCA study to be answered. As discussed in section 3.6, a range of different approaches and resources have to be used. As a consequence of time constraints and varying source quality, the study only concerns emissions to air.

It is difficult to arrive at any reasonable conclusions by comparing plastic and steel DH pipes without a rather well-defined context.That is why in this project the LCA method is applied to a specific case with a specific functional unit. There are many possible alternative comparisons to be made or different scenarios that could be used to answer the research questions. Ultimately the conditions described in section 5 are chosen with the ambition of providing a good balance of general and case specific results and conclusions.

To get acquainted with the project and its background, in-house reports by Kraftringen detailing the LTDH network were read. To further the understanding of the LCA domain and in particularity the work done in district heating area, old articles covering similar topics were read. Gradually as the system layout became more well-defined, reports and articles detailing characteristics of components and LCA related data on a process based level were also used.

Certain parts of the life cycles, more specifically the manufacturing and installation phases were available for firsthand examination. A visit to the Logstor headquarters and production facility in Løgstør, Denmark was made which included a tour of the manufacturing lines for the two products. several visits to the construction site at Brunnshög, Lund took place to gain a better understanding of the installation process as well as to collect relevant data.

To process the large amount of data collected and to create a model of the studied system, the software OpenLCA was used. OpenLCA is an open source and free of charge software for life cycle modelling developed by Green Delta, a sustainability-consulting company based in Berlin, Germany. Founded on the principles of accessibility and community participation, OpenLCA provides a powerful tool for anyone conducting LCA studies.

As for the choice of an LCA database and impact assessment method, *Product Environmental Footprint* (PEF) was selected. PEF is an LCA methodology created by the European Commission's Joint Research Center (JRC). The designated OpenLCA version of the database is free of charge, has a midpoint approach and provides LCI data from many different domains as well as a selection of the most common LCIA categories. With the aim of providing companies and other organisations active within the EU with a common and well structured approach to LCA, the desired result is a means to " - *assess, display and benchmark the environmental performance of products, services and companies*" [15]. In this report, the method is either referred to as PEF or EF.

The choice to use OpenLCA and PEF is one made out of monetary convenience and not out of any particular traits or exclusive functionalities related to the software or LCIA method/LCI database. The complications inherent to the use of free-to-use software and data is discussed further in section 9 *Discussion*.

Another program used during the project is the *Logstor Calculator*, which calculates, among other things, the heat loss of the pipes available in their catalogue when providing it with case specific input.

When conducting an LCA it is important that the collected data uphold to a certain standard. The quality of the data can be judged based on several parameters. The most important for this project are mentioned and commented on below. Generally, data procured through direct contact with core stakeholders are prioritized. There has not at any stage been made a deliberate choice to select one of source of information or type of data with the intention of creating an advantage or disadvantage for any of the two product systems.

- **Time-related coverage:** The ambition has been to collect as recent data as possible to be able to give a system representation which most amply represents the current conditions and circumstances. There is usually a delay of a couple of years between the year the data represent and the time of publication. This is normal in the LCA domain. The gathered information in this report originates almost exclusively from the previous decade (2010's), with 2015 as an appraised median year.
- **Geographical coverage:** The main ALCA and its associated LCI data are regionally limited to Europe. The parameter analysis examines other regions of the world but this section is treated as a separate entity and a complement to the main study. When possible and applicable, values pertaining to specific areas are used in the model. One such example is the electricity mixes for Sweden and Denmark which have been modelled independently.
- **Technology coverage:** Activities and processes have been modelled as accurately as possible in regards to the technology and resources that constitute them.
- **Consistency and sources:** Concerning the use of background data, only the PEF database available in OpenLCA is considered. This is made with the intention to assure a consistency in the data collection procedure for processes with less insight than the ones associated with and readily available through collaborators closely related to the study.

A couple of diversions from the data quality guidelines are made but only used when the data category at hand is known to have a very small impact on the final result and when there is no other apparent way of avoiding a zero-value assumption, i.e. ignoring the effect of a process altogether.

5 Case Description

5.1 Functional Unit

Normally, the functional unit is decided in advance to act as a basis of comparison to evaluate the performance of and requirements on the different products or systems considered in the LCA. This is the correct systematic approach and it works well when the ambition is to find the best contender for the fulfillment of a certain need or function.

In this particular case the explicit intention was from the start to compare district heating pipes with carrier tubes made from plastic and steel respectively. A certain need was never officially specified. It was clear, from Kraftringen's standpoint, that the two product series could be used interchangeably in many different situations. There were thus several possible functional units available.

In order to create a functional unit, the problem had to be reverse engineered. An area, Skymningen, under construction in Brunnshög was selected as a reference. The neighborhood had a projected heat consumption corresponding to a commonly used pipe size in a DH network. The size of the pipe was appropriate since it would be a good average dimension to represent the network as a whole. Further benefits of this area were the length of the planned trench, measuring around 120 meters and that the system would have a good amount of incorporated bends and joints. In today's DH pipe ecosystem, pipes are in certain dimensional ranges available in either "single" or "twin" format. Both versions could be considered viable options to fulfill the imposed requirements. However as the inclusion of both types would greatly enlarge the studied system without presumably providing a clearer answer to the main question, the choice was made to focus on the more common single-pipe series. It should be noted that the single-pipe system uses one supply pipe and one return pipe. For one stretch of trench, the double amount of pipe, lengthwise, will be needed.

The buildings connected to this branch of the network have an estimated collective heat consumption tabulated below.

Table 4: Estimated heat consumption of buildings connected to the studied district heating branch.

Building	**MWh/year**
LKP AB	140
LKF	360
Hauschild and Siegel	150
Slättö	170
Total	**820**

A visual representation of the functional unit is displayed in figure 5. The studied district heating branch begins at the letter A and ends at the letter B. With the intention of a clearer image, the figure only displays one of the supply or return branches. The second one runs in parallel. The blue lines represents the main path and sometimes exclusively the steel DH pipe path. The green dotted lines are the stretches the PE-RT pipe system takes when diverging from the steel system. Yellow and red represent the T-joints and steel bends respectively. The pink lines are the pipes connecting the main branch to the buildings. They are not included in the study.

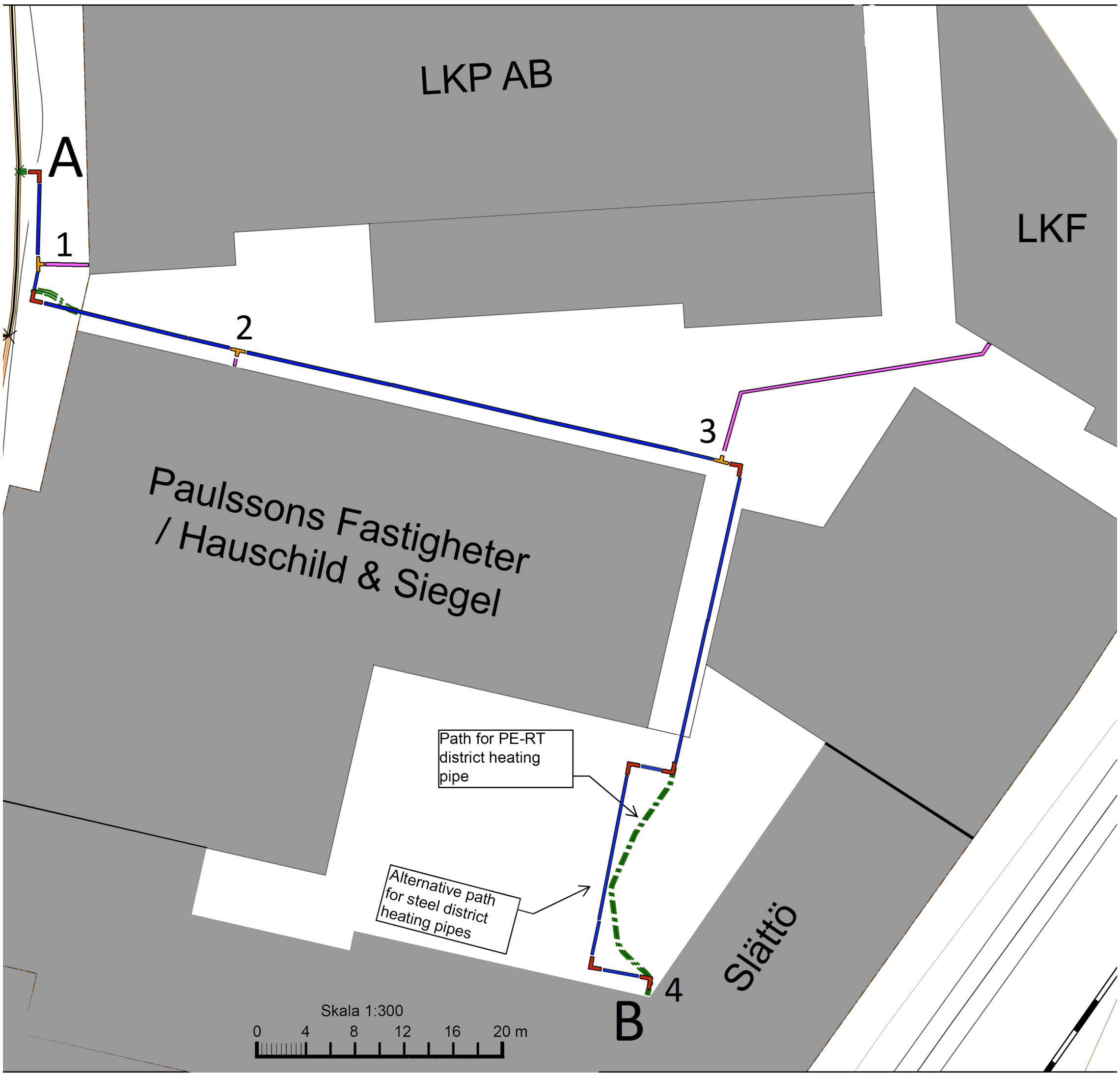

Figure 5: A preliminary layout of the DH branch and its connections at the neighborhood Skymningen at Brunnshög.

The total lengths of the two pipe systems could be expressed as:

$$\textbf{Steel:} \quad 2 * (8.8 * l_{pipe} + 7 * l_{bend} + 3 * l_{Tjoint}) = 2 * (8.8 * 12 + 7 * 2 + 3 * 1.2) = 246.4\ [m]$$

$$\textbf{PE-RT:} \quad 2 * (1.1 * l_{pipe} + 3 * l_{Tjoint}) = 2 * (1.12 * 100 + 3 * 1.2) = 231.2\ [m] \tag{1}$$

The expressed lengths l_{pipe}, l_{bend}, l_{Tjoint} used in equation 1 represent the unit length of components included in the DH branch and are found in table 5.

The flexibility of the PE-RT system allows for a shorter pipe system which complicates the functional unit, or at least makes it more diffuse.

Using this neighborhood as a reference, the functional unit could finally be formulated as:

Functional Unit: *District heating single-pipe system, supply and return, an approximately 80 millimeter inner diameter and able to deliver an estimated amount of 820 MWh of heat per year.*

5.2 System Boundaries

This report examines two types of district heating pipe systems with equal functionality. There are other similar products that could have been included in the study which could have had a significant impact on the end result. Ultimately, due to this being a case study, only the two options actually considered by Kraftringen for this application were included. They are both produced and supplied by the same company Logstor which to some extent limits the range of possible scenarios leading up to the delivery of the product to Kraftringen.

The study includes the entire life cycles of each product system with the exception of recycling. This phase of the life cycle was assessed to be unrepresentative of the real life scenario since energy companies allegedly do not unearth installed DH pipes after decommissioning. Consequently, details regarding the recycling procedure of DH pipes and materials are limited and can not be presumed to meet the same standard as the data and information concerning the other life cycle phases.

The two product systems have a techno-economic life time of 30 years according to Kraftringen. This is the time span assumed for the use phase. Given the DH network specifications, the pipe manufacturer confirms a longer possible life time for both systems. This is further investigated in the parameter analysis.

To keep the LCA study focused on the discussed product systems, only material, energy and activities directly contributing to the existence and performance of the products are considered. This entails disregarding the impact of things such as heating and lighting for production facilities as well as degeneration of equipment and machines.

The studied life cycles are assumed to follow a theoretically perfect scenario where no mishaps, disturbances or unforeseeable events occur. Included in this category are, among other things, damaged pipes in need of service, interruptions in production lines and detours during transportation.

The PEF LCIA method used in the model belongs to the midpoint category and consequently long-term implications such as damaged ecosystems and habitat changes are not included in the study. Moreover, aesthetics and noise pollution are not considered.

6 Inventory

The Inventory's purpose is to describe the product systems and their different life cycle phases as well as account for the designated emissions.

A product's life cycle can be divided into phases, most of them starting with resource extraction and many ending with recycling. Based on the scope of the study, which parts are included can vary. This project, as defined in the LCA scope (section 5), covers the life cycle phases starting from resource extraction all the way to the use phase. As stated in the scope of the study, recycling is not included. The general life cycle is illustrated in figure 6.

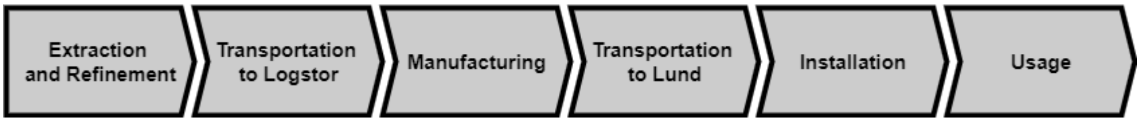

Figure 6: The general layout of the examined system's life cycle.

Each subsection describing a life cycle phase is completed by a table (blue header) registering the emissions of carbon dioxide, sulfur dioxide and nitrogen oxides measured in kilograms. These three molecules are powerful driving forces in LCIA categories such as *Global Warming Potential*, *Acidification* and *Eutrophication*. Their individual contributions to the LCIA categories do not represent the system as a whole and the impact assessments (section 7) are based on a much larger quantity of data categories. These tables are simply meant to provide an appreciation for the relative weight of the different life cycle phases. It should also be noted that processes from secondary data (i.e. EF database) sometimes differentiate between molecules of the same type based on how and where they are emitted. The LCI tables with blue headers only display the amount from the most common group of emissions to air (in the PEF directory labeled "*Emission to air, unspecified*") and may therefore overlook the presence of some types of CO_2, SO_2 and NO_x. Furthermore, the NO_x category as presented in the tables include NO_2, even though they may from time to time be presented individually. Nonetheless, everything is still accounted for in the final LCIA.

6.1 Product Description

The two pipes considered in this LCA are: 1. *Flextra PE-RT single 110* and 2. *DN80, insulation series 2*. In the report the former is often simply referred to as "PE-RT" or sometimes "plastic" and the latter to as "steel". A rule among district heating manufacturers state that products with a plastic carrier pipe be denoted by the outer diameter of the carrier pipe, while in the steel case the inner diameter is used. Their characteristics and general information are listed in the table and figures below. [25]

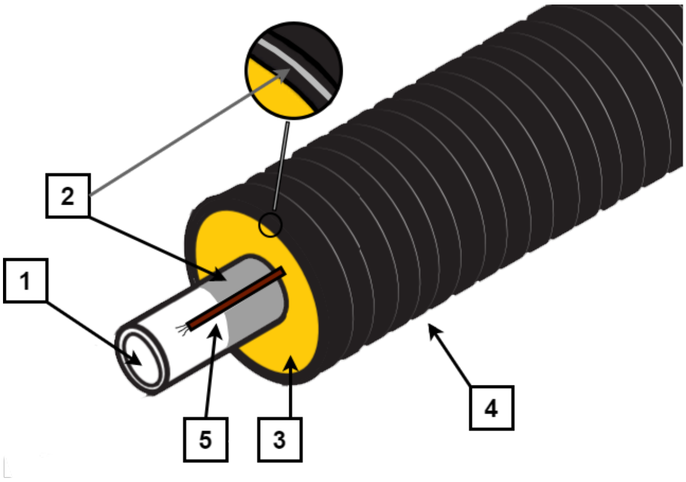

Figure 7: Cross section of the PE-RT DH pipe. 1: PE-RT Carrier Pipe, 2: Diffusion Barrier, 3: PUR Foam, 4: Corrugated PE Casing, 5: Copper Surveillance Wire. [25]

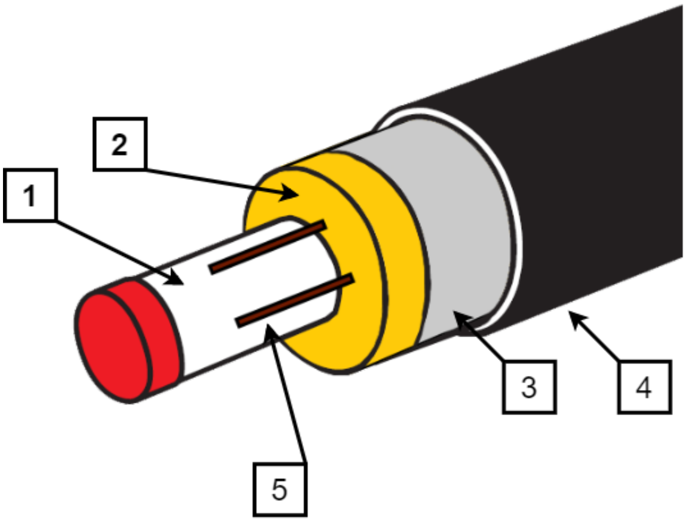

Figure 8: Cross section of the Steel DH pipe. 1: Steel Carrier Pipe, 2: PUR Foam, 3: Diffusion Barrier, 4: PE Casing, 5: Copper Surveillance Wire. The red end cap is not included in the study. [25]

The carrier pipe (also known as service or medium pipe) transports the district heating water and has to be able to resist decades of high pressure and thermal stress. The insulation reduces the amount of heat loss to the surroundings. It is made from polyurethane foam in which tiny bubbles of cyclopentane (gas) are chemically infused. Since heat, in the case of thermal conduction, is transferred through the movement of colliding molecules, the gas (being less dense than the surrounding solid plastic) radically limits the rate of heat transfer [26]. The diffusion barriers are meant as a way to limit the diffusion of the cyclopentane and to stop moisture from reaching the insulation since its performance is closely related to its level of dryness. It also prevents oxygen from reaching the steel pipe which limits the presence of corrosion. The HDPE casing (also know as jacket pipe or mantel) acts as a hard shell with the purpose of protecting the inner parts from physical damage as well as giving structural rigidity to the system. Finally, the copper wires are part of a surveillance unit meant to detect leakages. A current is passing through the electrodes and in the case of water entering the system a short circuit will occur. This works a bit differently for the two product systems. In the steel alternative the steel pipe acts as ground while for the PE-RT, a third copper wire acts as ground.

Table 5: Description of components constituting the two product series. [25]

	Flextra PE-RT 110 (Plastic)	**DN80, Insulation Series 2 (Steel)**
General		
Unit Length [m]	100	12
Number of Units per Functional Unit	2.24 (3)	17.6 (18)
Unit Weight [kg]	~811	~120
Outer Diameter [mm]	180	180
Expected Service Lifetime [years]	30	30
Carrier Pipe		
Material	PE-RT	Steel P235GH
Weight per Unit Pipe [kg]	490	81
Inner Diameter [mm]	79.8	80
Thickness [mm]	15.1	3.2
Insulation		
Material	Polyurethane Foam	Polyurethane Foam
Blowing Agent	Cyclopentane	Cyclopentane
Weight per Unit Pipe [kg]	143 [a]	16 [a]
Thickness [mm]	~33.3 [b]	42.6
Mantel		
Material	Polyethylene HDPE	Polyethylene HDPE
Weight per Unit Pipe [kg]	131	20
Thickness [mm]	1.5	3.0
Electrodes		
Material	Copper	Copper [c]
Size [mm^2]	3*0.6	2*1.5
Weight per Unit Pipe [kg]	2.3	1.5
Diffusion Barrier		
Material	Aluminium Foil	Aluminium Foil
Weight per Unit Pipe [kg]	4.3	0.9
Miscellaneous		
Number of T-joints	6	6
Number of bends	-	14
Number of SX-WP joints	-	50
Number of B2S Reductions	14	-
Number of Brass Couplings	22	-
Number of Foam Packs	22	50

[a] *Accumulated weight of components, no loss of material is assumed*
[b] *Estimated thickness since the outer casing is corrugated*
[c] *One wire is made of pure copper while the second is tin-infused*

Table 5 presents information regarding the constituents of the two product systems. Information stems from Logstor's product catalogue for district heating components [25] and from the data shared by Logstor during the visit to their facility. It is important to note the difference between "unit" which represents one produced district heating pipe and "functional unit" which loosely (in an LCA sense) represents the entire final system. The number of DH pipe units required to fulfill the functional unit is represented by two numbers. The first represents the actual amount needed while the second one within parentheses is the total number of units that has to be purchased. Leftover pieces of steel DH pipe above 3 meters in length and 10 meters in the PE-RT case can be reused for other parts of the DH network. Consequently, the scrap segments are not allocated to the examined system.

For the sake of a cleaner table, the diffusion barriers are explained here. The steel pipe has a diffusion barrier placed between the insulation and the outer casing. It is made from an aluminum sheet encapsulated in between two very thin layers of transparent polyester. The PE-RT pipe has the same type of diffusion barrier around the carrier pipe which in turn is covered by a small layer of the same PE-RT material used in the carrier pipe. Furthermore, the PE casing in the plastic pipe case has an infused diffusion barrier of the same material as the others. It is also worth noting that the T-joints as well as the steel pipe bends do not have diffusion barriers.

6.1.1 T-joint

The T-joint is the component that, in this scenario, connects the main DH network with each separate building. For each connected building there are two T-joints, one connected to the supply branch and the other one to the return branch. It is prefabricated and has the same characteristics and components as the steel DH pipe. It is manually TIG welded at the ninety-degree intersection. The length L_1 of the main branch is 1,2 m while the offshoot L_2 is 600 mm. Currently a dedicated T-joint does not yet exist in the PE-RT line of products. Instead, a T-joint from the same product series as the one in the steel system is used. However, the carrier pipe in the PE-RT case is larger than the corresponding one in the steel case. Therefore, a T-joint with a larger carrier pipe diameter has to be used. A specific plastic to steel coupling connects the PE-RT and steel sides (see section 6.1.4).

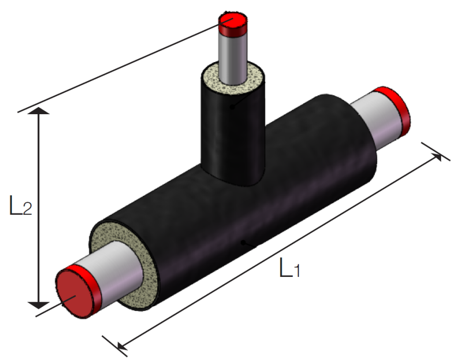

Figure 9: Steel T-joint. L_1=1200 mm, L_2=600 mm. [25]

Table 6: Main components of the T-joint. Two dimensions are listed, one applicable to the steel product system and the other to the plastic product system.

		Steel Case			PE-RT Case		
	Material	**Weight [kg]**	**d_1 [mm]**	**d_2 [mm]**	**Weight [kg]**	**d_1 [mm]**	**d_2 [mm]**
Carrier Pipe	Steel P235GH	12.8 [a]	88.9	88.9	19.6 [a]	114.3	114.3
Insulation	PUR Foam	2.2			3.6		
Mantel	HDPE	3.2 [a]	180		4.8 [a]	225	
Surveillance Wire	Copper [b]	0.32 [a]			0.32 [a]		

[a] *Estimated values based on the corresponding components of the main DH pipe*
[b] *Tin-infused copper*

6.1.2 Bend (Steel Case)

The prefabricated bend unit is only applicable to the steel pipe system. It shares the same characteristics and structure as the main steel DH pipe. It is manually TIG welded. The length L of each arm is 1 m.

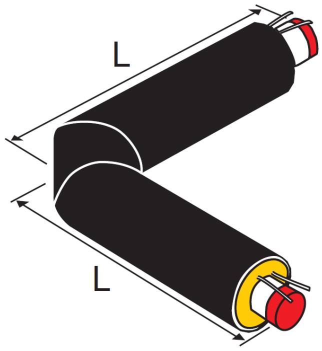

Figure 10: Ninety-degree steel bend. L_1=1000 mm. [25]

Table 7: Main components of the ninety-degree steel bend.

	Material	**Weight [kg]**
Carrier Pipe	Steel P235GH	12.6 [a]
Insulation	PUR Foam	2.2
Mantel	HDPE	3.2 [a]
Surveillance Wire	Copper [b]	0.3 [a]

[a] *Estimated values based on the corresponding components of the main pipe*
[b] *Tin-infused copper*

6.1.3 SX-WP Joint

The unit acts as a bridge between the ends of two pipe units. The SX-WP joint is used in both studied product systems and weigh around 1.6 kg in an unfilled state. The shrink sleeve (main body) is made from cross-linked polyethylene (PEX). The venting and weld plugs are not considered in this study. The item is supplied in its complete and final form to Logstor, Poland by a company in the close vicinity.

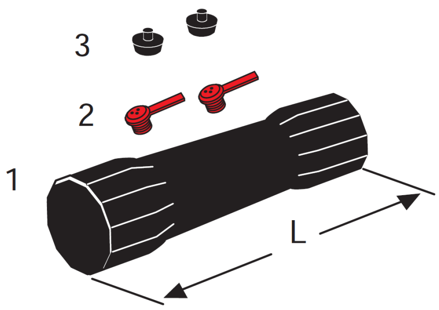

Figure 11: SX-WP Joint. L = 650 mm. 1: Shrink Sleeve, 2: Venting Plugs, 3: Weld Plugs. [25]

6.1.4 B2S Reduction (Plastic Case)

To connect the T-joint which has a steel carrier pipe with the PE-RT pipe, a B2S reduction is used. Even though the outer diameters of the two considered DH pipes systems are equal, the carrier pipes do not match resulting in the use of a larger t-joint and a B2S reduction on each side of the t-joints main branch. The main body of the unit is made from HDPE granulate and the weight of an unfilled B2S reduction is 2.5 kg. Only the shrink sleeve is considered in this study. The unit is produced at the Logstor facility in Poland.

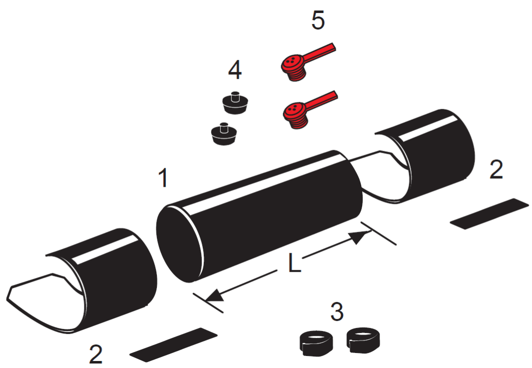

Figure 12: B2S Reduction. L = 700 mm. 1: Shrink Sleeve, 2: Shrink wrap with closure patches, 3: Sealing Tape 4: Weld Plugs, 5: Venting Plugs. [25]

6.1.5 Brass Coupling

Unlike the steel pipe system where the connection between two neighboring units is created through a welding process, the PE-RT pipes use prefabricated brass couplings that connect through compression. At a PE-RT to PE-RT junction the *110x110 Compression coupling PN10* is used. Video material explaining the technique is available at the Logstor website [27]. As for the connection between a PE-RT pipe and a steel T-joint, another type of coupling is used where the PE-RT side is compression based and the steel side can be welded. The brass is so called "dezincification resistant brass" (DZR) which is better adapted to corrosive environments [28].

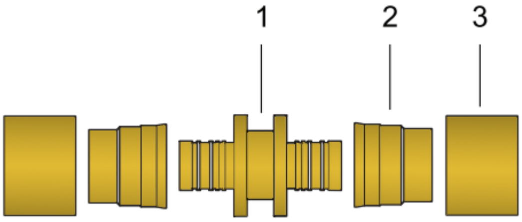

Figure 13: Brass compression coupling PN10. 1: Supporting Bush, 2: Squeezing Ring, 3: Press Ring [25]

Table 8: Material and weight for the two types of brass couplings.

	Material	Weight [kg]
110x110 Compression coupling PN10	DZR Brass	3.4
110x4" Compression - Weld PN10	DZR Brass	3.4

6.1.6 Foam Packs

Foam packs are used to create PUR foam in the cavities in SX-WP or B2S joints. They contain the three main components in PUR foam, isocyanate kept in one separate pouch and polyol and cyclopentane kept in another separate pouch. The ratios and exact type of chemicals vary for each application. The plastic pack is not included in the study. The unit is produced at the Logstor facility in Poland.

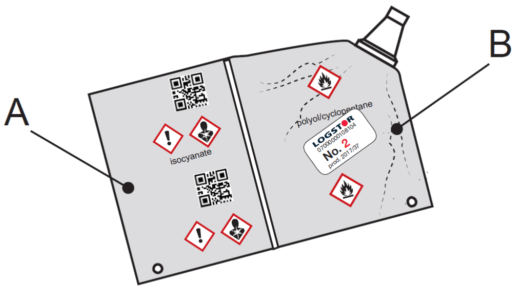

Figure 14: Depiction of a generic foam pack. A: Isocyanate, B: Polyol and Cyclopentane [25]

6.2 Resource Extraction and Processing

The sheer amount of components and materials involved in this study prevents everything to be accounted for, even more so, everything to be described in written text. For this reason, this section is only focused on detailing the main components of the pipes and their respective origins. The given name to the current life cycle phase implies a distinct delimitation between acquiring and processing raw materials and the production of goods. However, the choice made in this report is to let everything leading up to the point where Logstor becomes directly involved be included in this phase. The ensuing *Manufacturing* phase revolves around the activities at the Logstor production sites. Consequently, the creation of products like welded steel pipes and plastic granulate are according to this reasoning all covered in this section.

6.2.1 Steel

The DN80 steel carrier pipes used in Logstor's products are produced in northern Italy. Generally, this case included, the steel is produced elsewhere and delivered to the steel pipe manufacturer in the shape of a large steel coil.

Starting from the beginning, the main resources iron ore, bituminous coal and limestone are all extracted at their respective quarries. One part of the iron ore is turned into iron pellets through a process known as pelletization while another part, together with the limestone, is turned into sinter. The coal is processed into coke which acts as the main fuel source in the blast furnace. At an elevated temperature of around 1600 °C, sinter, coke, pellets and lime are mixed to create pig iron. Steel is then created in either a basic oxygen furnace (BOF) or an electric arc furnace (EAF). Through secondary metallurgy and hot rolling operations, hot rolled coil is produced. The operation is depicted in figure 15.

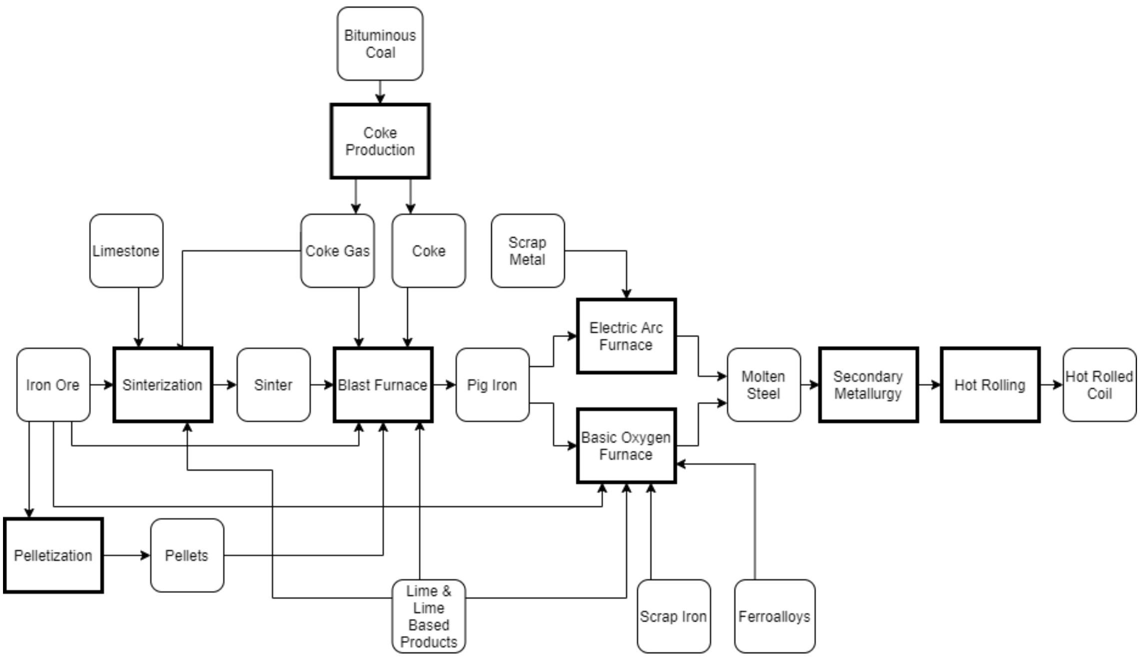

Figure 15: A simplified illustration of the cradle to gate production of a hot rolled steel coil. The layout of the flow chart is based on information from an LCA regarding Italian steel production [29] as well as video material from steel producers in Mexico [30] and the United States of America [31].

At the steel pipe manufacturer the hot rolled coil is continuously drawn through a series of rollers giving it a circular shape which is then sealed in a welding operation [32].

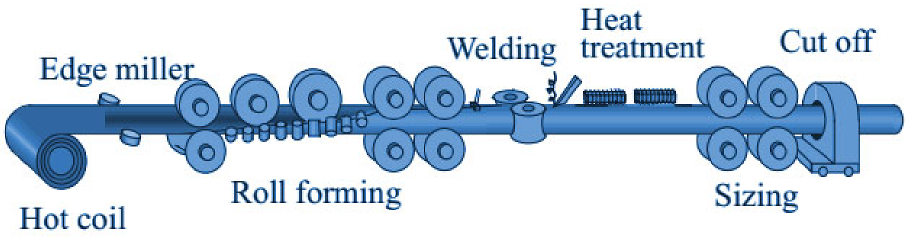

Figure 16: Electric resistance welding process of a steel pipe. [33]

The LCI data used for the main ALCA scenario is provided by the World Steel Association [34] and represent the average value of fifteen different producers in Europe.

6.2.2 PE - *Polyethylene* - Granulate

Neither the PE-RT nor the steel product systems actually contain any major components made from basic polyethylene granulate. However, special versions like *High Density Polyethylene* (HDPE) and *Polyethylene of Raised Temperature* (PE-RT) are crucial input materials.

HDPE is the main material in the outer pipe casing in both systems. It is highly crystalline and the polymer chains are densely packed. It therefor has, as the name implies, a high density. Other qualities include good mechanical strength and temperature resistance. [35]

PE-RT is the material constituting the carrier pipe in the PE-RT system. It boasts great long-term strength and high temperature resistance. These qualities are due to the incorporation of co monomer side chains attached to the main polymer chains which in turn create imperfections in the crystal lattice improving the material's mechanical traits. This should not be confused with cross-linked polyethylene (PEX) where the side chains are directly connecting the main polymer branches with each other. PE-RT also exhibit better creep properties at high temperatures than HDPE, making it a more suitable alternative for district heating applications. [36]

Held in common by HDPE, PE-RT and other members of the PE family is the cradle to gate supply chain that they share up until the polymerisation step. Since most of the impact is deemed to be located in the earlier steps of PE life cycle and because specific LCA data for PE subgroups are hard to come by, every PE-derived material except HDPE are modelled as standard PE granulate. Figure 32 depicts a general polyethylene production process.

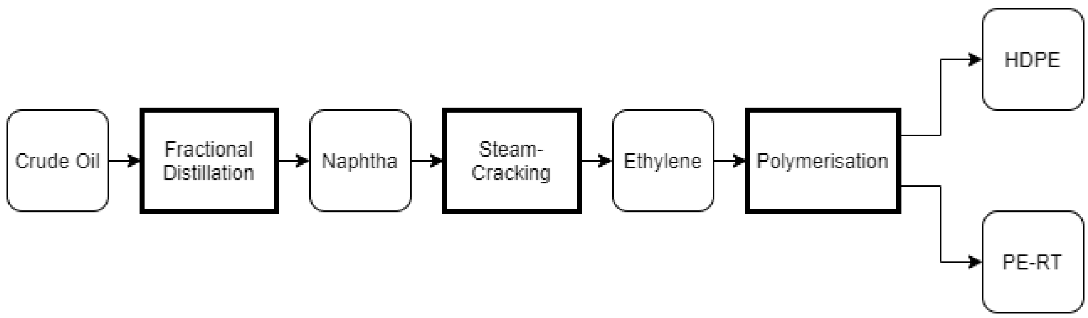

Figure 17: Cradle to gate sequence of PE.

Ethylene is traditionally produced through the processing of crude oil derivatives, more specifically naphtha. Fractional distillation is a method for separating carbon-hydrogen chains of different lengths from each other. The subsequent steam-cracking procedure has a similar function in which it breaks the chains into even smaller molecules, for example ethylene. The main ALCA scenario investigated in this report is based on the oil product line.

6.2.3 PUR - *Polyurethane* - Foam

Polyurethane (PUR) is a polymer with a foam like structure that in district heating pipes fulfills the function of thermal insulation. Generally it is produced by mixing the two main ingredients diisocyanate and polyol. In DH applications a blowing agent, in this case cyclopentane, is entered into the mix as a way to ameliorate the overall thermal insulation capacity of the foam. In order to control the polymerisation process, a catalyst is added.

The PUR foam is not supplied in its final shape to Logstor. Instead, the chemicals are acquired separately and processed during the continuous assembly of the DH pipes. Therefore, based on the structure of the inventory in this report, the correct subjects pertaining to this subsection are the chemical constituents.

Isocyanates are organic compounds defined by their functional group R-N=C=O, where diisocyanate have two of these functional groups. They are produced through a series of reactions and intermediate steps, the closest precursor being the phosgenation of amides [37]. There are different variants of isocyanates and the one used for the modeling of this life cycle is diphenylmethane diisocyanate (MDI) which is commonly used in this area.

Polyols, or more specifically in the context of district heating: polymeric polyols, are also organic compounds and are defined by the functional group OH. So called long-chain polyols are used in PUR foams for thermal insulation applications due to their low density which subsequently reduces the material's thermal conductivity. Its origins are normally traced back to fossil resources but there are possible ways of producing the chemical through renewable means.

Cyclopentane is a gasoline derivative with the chemical formula C_5H_{10}. It can, for example, be produced through fractional distillation of partially hydrogenated pyrolysis gasoline[38].

Unless stated otherwise, descriptive information presented in this section is based on a doctoral thesis regarding insulation materials in DH pipes [26]. LCI data from the EF database [39] is used to model the cradle to gate life cycle of diphenylmethane diisocyanate and long-chain polyols. An article on LCA of district heating pipe production [6] provides LCI data for Cyclopentane and a DH industry generic PUR catalyst.

6.2.4 Copper

Copper is an element normally found in copper-bearing ores. Due to its low concentration per unit area, a mining method called open-pit mining is usually deployed. Subsequently, on the road to become high purity copper cathode, the ore can be processed in one of the following ways, *pyrometallurgy* or *hydrometallurgy*. These two approaches are made up of a set of processes which turns ore with a 30 percent copper content into 99.99 percent pure copper.

The copper cathodes are then melted and turned into copper rod. To attain the final dimension of the desired copper wire, the rod is drawn through a series of die where the diameter of the rod is reduced with each pass-through.

The data and information related to this section comes from the report *Copper Environmental Profile* provided by the International Copper Association [40] as well as the EF database [39].

6.2.5 Aluminium

The first step of aluminium production is the extraction of Bauxite, an aluminium-rich mineral which is commonly mined in so called open-pit mines. The mineral is then ground, washed and dried. It is then put through a so called Bayer process which through mixing, chemical reactions and high pressure at elevated temperatures produces precipitated aluminium oxide (Al_2O_3) or alumina for short. Following on from there, the alumina is processed through an electrolytic reduction cell which effectively splits the aluminium from the oxygen leaving molten aluminium which is subsequently cast into iron ingots.

At the aluminium foil factory, the ingot is continuously flattened in a series of hot rolling and then cold rolling procedures.

The process description of the cradle to gate life cycle of aluminium cathode and gate to gate life cycle of aluminium foil is provided by The Aluminum Association [41] and the EF database [39]. The data used in the model comes from the EF database [39].

6.2.6 Summary: Resource Extraction and Processing

Table 9: Summation of the emissions related to the activities during the resource extraction and refinement phase. The emissions carbon dioxide CO_2, sulfur dioxide SO_2 and nitrous oxides NO_x are measured in kilograms.

	PE-RT			Steel		
	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x
PE-RT Granulate	2 029	2.75	3.73	-	-	-
Steel Pipe	282	0.39	0.42	4 057	5.67	6.08
HDPE	648	0.89	1.19	737	1.01	1.33
Isocyanate	739	2.54	1.79	725	2.49	1.76
Polyol	232	0.40	0.46	235	0.41	0.48
Cyclopentane	13	0.05	0.07	11	0.04	0.06
Copper	8	0.27	0.15	131	1.43	0.57
Aluminium	88	0.16	0.11	136	0.25	0.17
Total	**4 039**	**7.45**	**7.92**	**6 032**	**11.30**	**10.45**

6.3 Transportation to Logstor

The different components constituting the two final product systems are supplied by a wide range of companies scattered across central and western Europe. The units and materials are shipped to either Logstor, Denmark or to Logstor, Poland for the final manufacturing processes and assembly. Everything but the SX-WP-joint, B2S Reduction-joint and the foam packs are shipped to Logstor in Denmark. A list of delivery amounts, means of transportation and distances covered, is presented in table 10.

Based on information provided by Logstor, shipments are either carried out by tank trucks (chemicals) and heavy duty trucks with a capacity of carrying 33 euro pallets. Using the shipment sizes as a reference it is deduced that both vehicle types can be modeled (emission wise) as a heavy duty vehicle, class >32 tonnes, the latter with a payload capacity of 25 tonnes [42]. Both are assumed to be diesel powered. The emission standards of different vehicle categories are dictated by EU legislation where the current one since 2013, related to heavy duty vehicles, is the Euro VI [43]. Further, it is assumed that the payload is 61 percent [44] and that each component is delivered separately, i.e. one truck for each component.

In this report the emission of a certain component or material X due to a transportation activity is calculated using the formula:

$$E_X = EF_x * D * AF \quad [\mathrm{g}] \tag{2}$$

Where:

E_X = emission of X [g]

EF_X = emission factor of X [g/km]

D = distance covered during transportation [km]

AF = Allocation factor for considered product

The emission factors for CO_2, CO, NO_x and PM 2.5 are based on data from [45], while emission factors for N_2O, NH_3, SO_2 and NMVOC are based on [43] which correspond to the EURO IV requirements. They are all displayed in table 11. Emission factors for N_2O and NH_3 are presented as NO_2 equivalents.

The material and components, meant for the considered product system, delivered by the lorry with a 33 pallet capacity, share the cargo space with other products. The emissions produced by the transport activity are allocated based on weight. The allocation factor for a component C then becomes:

$$AF_C = \frac{m_{C,FU}}{(25000 * 0.61)} \tag{3}$$

Where $m_{C,FU}$ is the weight of component C required to fulfill the functional unit, 25000 represents the presumed total payload capacity in kg and 0.61 is the average utilization factor. Furthermore, since the cargo space is shared with other items that are destined for other clients, the impact from presumable return trips are not considered in this report.

Table 10: Transportation of material and components to Logstor, Denmark and Poland.

Component	Amount/delivery	Transportation	Origin	Distance [km]
To Logstor, DK				
Steel Carrier Pipe	288-333 units	Truck [a]	Cremona, IT	1630
PE-RT Granulate	1 t	Truck [a]	Leipzig, DE	810
HDPE Granulate	24-26 t	Truck [a]	Vienna, AT	1350
Copper Wire (Steel)	1.92 t	Truck [a]	Chybie, PL	1280
Copper Wire (PE-RT)	0.8 t	Truck [a]	Borås, SE	740
Brass Couplings	100 pcs	Truck [a]	Noormarkku, FI	1120
Isocyanate	22-26 t	Truck [b]	Lemförde, DE	650
Polyol	21.96 t	Truck [b]	Lemförde, DE	650
Cyclopentane	15-20 t	Truck [b]	Algestrup, DK	380
Catalyst	1 t	Truck [a]	Lemförde, DE	660
Aluminium Barrier	18 km	Truck [a]	Horsens, DK	150
To Logstor, PL				
SX-WP joint	-	Truck [a]	n.a.	n.a.
HDPE Granulate (B2S) [c]	24-26 t	Truck [a]	Vienna, AT	390
Isocyanate [c]	22-26 t	Truck [b]	Lemförde, DE	890
Polyol	21.96 t	Truck [b]	Warszawa, PL	295
Cyclopentane [c]	15-20 t	Truck [b]	Algestrup, DK	934

[a] *Truck Type: Assumed to be a heavy duty articulated lorry > 32 t*
[b] *Truck Type: Tank truck*
[c] *Assumed to be the same supplier as the one to Logstor DK*

The SX-WP joint is marked "non applicable" in table 10 because it is fully produced and delivered in its final pre-usage form by a supplier in the close vicinity of the Logstor, Poland facility. Due to the negligible distance, it is not included in this segment. The distances presented in table 10 are based on data from Google Maps.

Table 11: Emission Factors for heavy duty vehicle >32 t, given as g emission/km.

Emission Factor [g/km]	CO_2	CO	NO_x	N_2O [a]	NH_3 [a]	SO_2	NMVOC	PM2.5
Value	776.61	1.05	0.48	0.05	0.01	<0.01	0.01	0.01

[a] *Given as NO_2 equivalents*

Table 12: Summation of the emissions related to the series of transportations of material and components to Logstor. The emissions carbon dioxide CO_2, sulfur dioxide SO_2 and nitrous oxides NO_x are measured in kilograms.

	PE-RT			**Steel**		
	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x
Transport to Logstor	74	«0.01	0.05	114	«0.01	0.07

6.4 District Heating Pipe Manufacturing

The process descriptions and details in this chapter are based on a tour of the production facility carried out October 8th, 2020 at the Logstor headquarters in Løgstør, Denmark. The two products are both manufactured at the site but in different buildings and at different production lines. Electricity is the only energy source used in the production. Only machines and equipment directly linked to the production of the pipes are included in this LCA. Heating of buildings, lighting and forklifts among other things are therefore not of interest to the assessment. The energy consumption for each of the main processes is based on measurements and estimations provided by people in charge of operations at the factory.

6.4.1 PE-RT DH Pipe Manufacturing

The PE-RT district heating pipe manufacturing process can be divided into two parts. The first, as illustrated in figure 18, concerns the production of the PE-RT carrier pipe. The second, figure 19, details the production and completion of the entire district heating pipe. Each process takes place in an automatic, straight and continuous line of production.

Granules are sucked up into a large funnel and inserted into the extrusion machine. Being pushed out, the now formed PE-RT pipe enters a segment where vacuum shapes it to its final form. Water Cooling ensues followed by the attachment of the diffusion barrier which is applied in a spiral winding motion. A small welding procedure connects the edges of the foil creating a seamless layer along the pipe. A second layer is applied around the diffusion barrier, this one made from a mix of the same PE-RT material as the carrier pipe and an additional polyester component. The pipe is then cooled with water and finally wound into a big spiral for temporary storage. The spiral shape is only meant to facilitate transportation and storage at the factory.

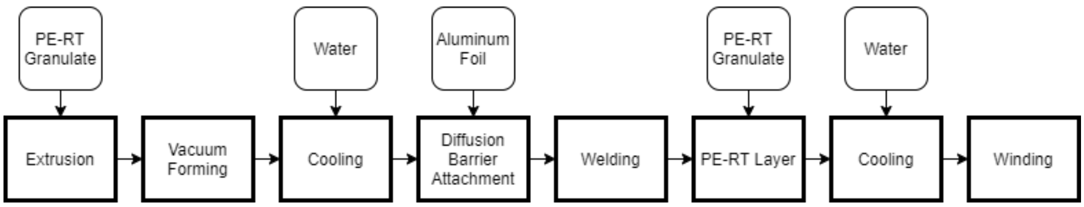

Figure 18: The manufacturing process of PE-RT pipes from granulate to winded pipe.

The pipe, at this point wound up, is pulled through a machine that through mechanical force straightens the pipe. Any static electricity is removed, this in order for the upcoming

PUR foam to better stick to the PE-RT pipe (more accurately, the PE-RT layer). The pipe is then heated. A thin plastic layer is drawn and formed into a cylindrical shell around the PE-RT pipe with a diameter equal to that of the final size of the PUR foam. It is thus not in contact with the PE-RT pipe. Simultaneously, the leakage surveillance unit is drawn alongside the pipe and the polyurethane is poured into the shell and left to expand and harden. The outer corrugated casing is extruded onto the PUR foam. Unlike in the case of the steel district heating pipe, the outer diffusion barrier is actually extruded concurrently with the PE casing and appears as a thin layer in the middle (radially) of the casing. The finished pipe product is then cooled and once again wound up for final storage.

At the time of the tour of the facility, the assembly of the PE-RT district heating pipe (the entire product, not the carrier pipe) production was momentarily not under way and the layout presented in the paragraph above represents a similar product with an almost identical manufacturing process.

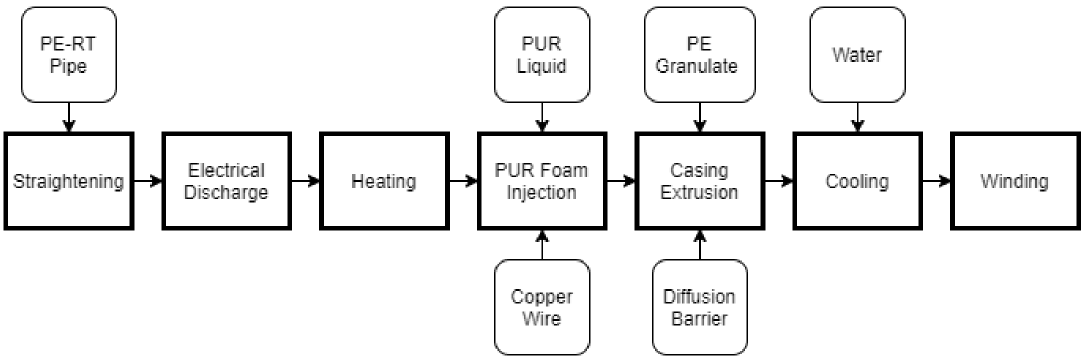

Figure 19: The manufacturing and assembly process of the PE-RT district heating pipes.

6.4.2 Steel DH Pipe Manufacturing

The steel pipes are acquired from a supplier and their production is therefore not presented here. Being stored outside, the steel pipes unavoidably begin to rust. A process known as shot blasting removes the rust by shooting tiny steel marbles at the pipe, effectively smoothing out the surface in an abrasive fashion.

The pipes are brought to another building where the main manufacturing line is located. The pipes come in different lengths (and sizes) equal to the length of the corresponding final product. However, since the production is continuous, the pipes are first taped together at the ends. Entering the production line, the steel is briefly heated by an induction warmer. Happening at once and in similar fashion to the PE-RT process, the diffusion barrier is drawn and the PUR liquid is poured. The copper wires also enter the picture at this point, being pulled along the pipe radially between the steel and the diffusion barrier. The PUR then expands and hardens, filling out the entire cavity between pipe and barrier. The smooth outer casing is then extruded onto the aluminum foil. Finally the pipe is cut back into its initial length and a 220 mm segment of foam, wires, barrier and casing is cut off on each side.

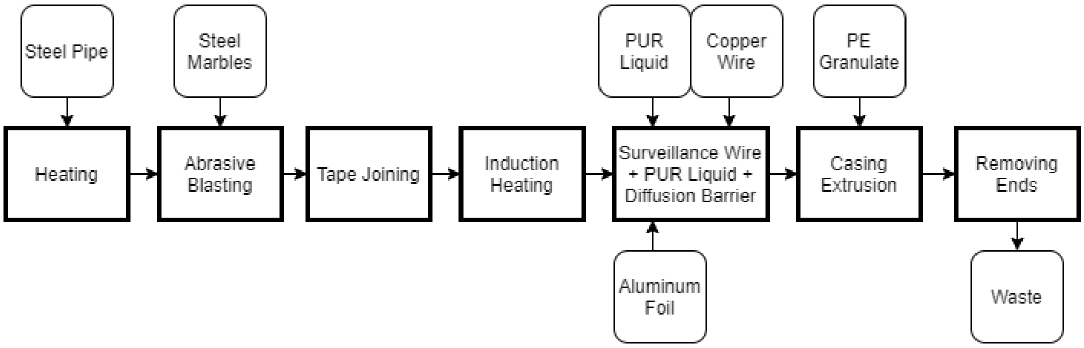

Figure 20: The manufacturing and assembly process of the steel district heating pipes.

6.4.3 Manufacturing of Additional Components

The ninety-degree bends and T-joints are, due to their irregular shapes, for the most part manually constructed. Manual TIG welding is used to fuse steel pipe parts together to create the directional changes. In similarity to the production of the main pipe units, the PUR foam is poured into the shell by the use of a machine. The PE mantel is attached to the carrier pipe through the use of so-called spacers. As mentioned earlier, bends and T-joints do not have diffusion barriers. Electricity consumption needed for the creation of these units is, as a consequence of the high level of manual labour, difficult to estimate but assumed to be the same as for the steel DH pipe on a per meter basis.

Detailed information regarding the manufacturing procedures of the SX-WP and B2S units has not been disclosed but their main bodies are extruded. The energy demand is not known either, instead secondary data from predefined extrusion processes have been used for modelling purposes.

6.4.4 Summary: Manufacturing

Table 13 displays the electricity need per produced pipe unit at the Logstor manufacturing facilities. As explained previously, the PE-RT manufacturing process can be divided into two major parts which are listed as two separate entries. The electricity used is modeled as domestically produced in Denmark and explained in greater detail in section 6.8.3.

Table 13: Energy consumption of production lines at Logstor, Denmark.

	Length [m]	kW	m/min	kWh/m	kWh/unit	kWh/FU
PE-RT Carrier Pipe	100	62.7	0.5	2.09	209	468
PE-RT DH Pipe	100	152	3.2	0.79	79	177
Steel DH Pipe	12	388	4.5	1.44	17	304

Table 14: Summation of the emissions related to the activities during the manufacturing phase. The emissions carbon dioxide CO_2, sulfur dioxide SO_2 and nitrous oxides NO_x are measured in kilograms.

	PE-RT			Steel		
	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x
PE-RT DH Pipe [a]	119	0.02	0.13	-	-	-
Steel DH Pipe	-	-	-	56	0.01	0.06
Steel Bend	-	-	-	7	<0.01	0.01
T-joint	3	<0.01	<0.01	3	<0.01	<0.01
SX-WP Joint	-	-	-	22	0.03	0.04
B2S Reduction	10	0.01	0.02	-	-	-
Total	**132**	**0.03**	**0.15**	**88**	**0.04**	**0.11**

[a] *Includes both "PE-RT Carrier Pipe" and "PE-RT DH Pipe" from table 13*

6.5 Transportation to Brunnshög, Lund

The final units in the two product systems are shipped to Lund from Logstor, Denmark and Logstor, Poland by truck. The covered distances are 470 km and 980 km respectively. The same type of vehicle as in section 6.3 is assumed. According to Logstor, all items in an order are delivered by the same truck. Since all components included in both product systems have an accumulated weight well within the trucks payload capacity, only one shipment each from the two Logstor facilities are included in the study. As is the case with the transportation of goods between suppliers and Logstor, the shipments to Lund are also joint deliveries. In other words, the cargo space is shared with other products and the same type of allocation as described by equation 3 is performed. This time the previously used $m_{C,FU}$ is replaced by the total weight of items shipped from either Logstor, Denmark or Logstor, Poland.

Table 15: Summation of the emissions related to the transportation of the final product systems to Lund. The emissions carbon dioxide CO_2, sulfur dioxide SO_2 and nitrous oxides NO_x are measured in kilograms.

	PE-RT			Steel		
	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x
Transport to Lund	49	«0.01	0.03	66	«0.01	0.04

6.6 Installation

The installation phase is divided into three parts: the trench excavation procedure, the construction of the DH branch and the trench restoration procedure. An overview of the phase is illustrated in figure 21. In contrast to other parts of the life cycle, the installation is one of a rather high level of uncertainty.

Compared to for example the manufacturing at Logstor, the installation is not really streamlined or continuous in the same way. There is obviously a certain order to things and a specific chain of events taking place but the high level of manual labour, varying weather conditions and different soil compositions (to name a few) implies a fair amount of unpredictability which directly affects the collection of LCI data. The bottom line is that estimations and assumptions are especially prevalent for this particular life cycle phase.

Trench dimensions for both cases are provided by onsite construction workers and data about standard trench layouts. Through simple calculations, cross sectional areas, volumes and masses can be derived. The method is provided in appendix.

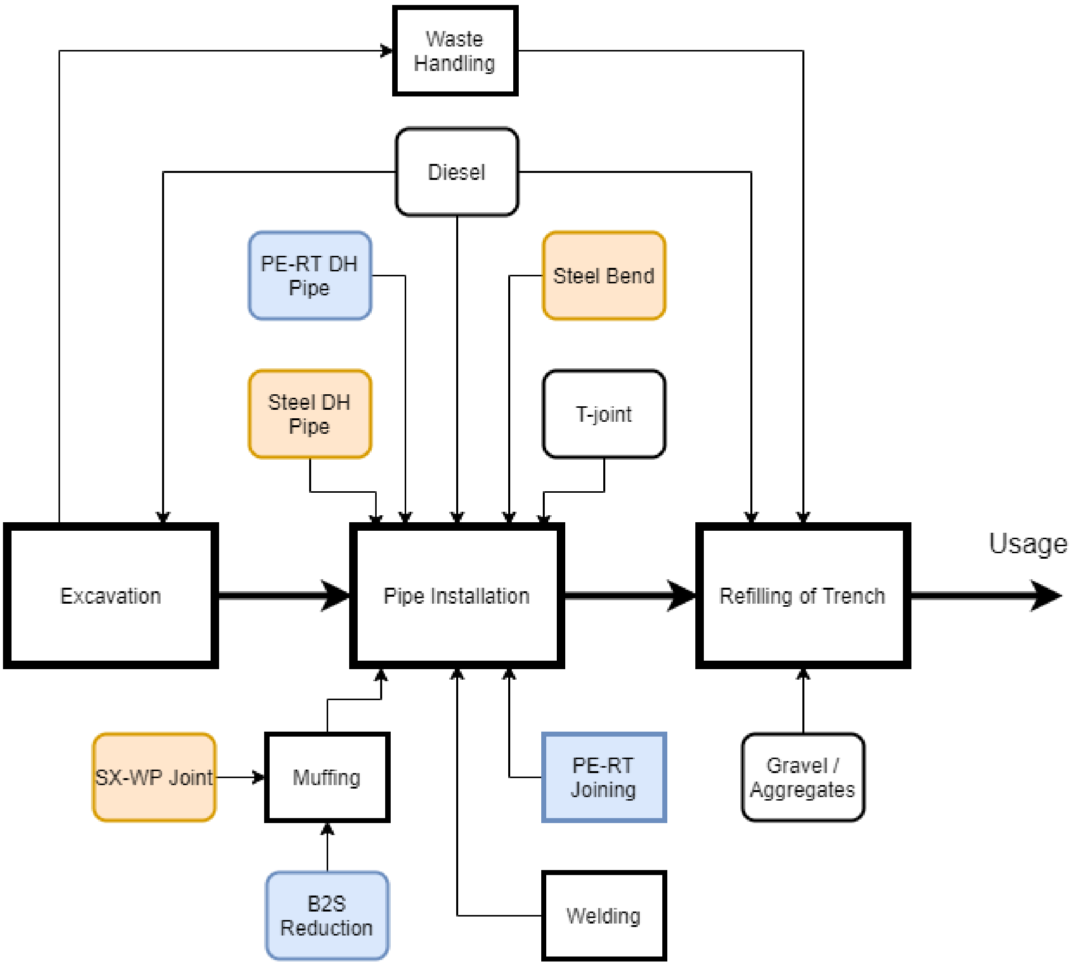

Figure 21: An overview of the installation phase of the DH pipe life cycle. Orange and blue boxes represent steel and PE-RT exclusive products or activities respectively.

6.6.1 Excavation

Based on the different models of excavators spotted at the construction site and specifications from manufacturers, reasonable characteristics were determined to be: weight 25-28 tonnes, engine output 130 kW and fuel consumption 11.77 L diesel/h. Through interviews with workers involved in the excavation process, it is estimated that 6 hours were needed to excavate a stretch of 100 meters. However, this estimation was based on the conditions of an adjacent construction site in Brunnshög and a trench with a smaller cross section. Previous studies on the subject [7],[9] differentiate between "green areas" (untouched land) and urban areas (existing infrastructure, e.g. paved road) when evaluating the time demand of the activity. Since the DH project at Skymningen contains elements of both categories, being built on previously untouched ground but concurrently being cramped into a confined urban area, it can not exclusively be branded as any one of them. Taking these facets into consideration, a period of 10 hours is assumed to provide a decent approximation of the time required to excavate the PE-RT trench length of a 115 meters. The corresponding trench for the Steel DH pipe system is both longer (123 m) and wider resulting in a factor 1.07 larger excavation volumes and subsequently an 11 hour period to carry out the excavation.

Due to the fact that the area Skymningen is an urban area, the excavated masses have to be displaced during the installation process. The deposit is located at Hofterup, 22 kilometers away from Brunnshög, Lund. A tipper or dump truck with a gross vehicle weight above 32 tonnes and an approximate cargo capacity of 20 tonnes per trip is used. Its characteristics are assumed to conform with the Euro VI emission standard and its emission profile correspond to the values presented in table 11. The soil or earth have an estimated bulk density of 1600 kg/m^3 [46]. Together with the calculated trench volumes, the total weight of the removed masses compile to 632 tonnes in the PE-RT case and 716 tonnes in the steel case, totaling in 32 and 36 trips to the deposit respectively. Unlike the case in section 6.3, these transports are solely intended for the displacement of excavated masses. As a result, no allocation procedure related to the cargo has to be done and both trips to and from the deposit has to be taken into account.

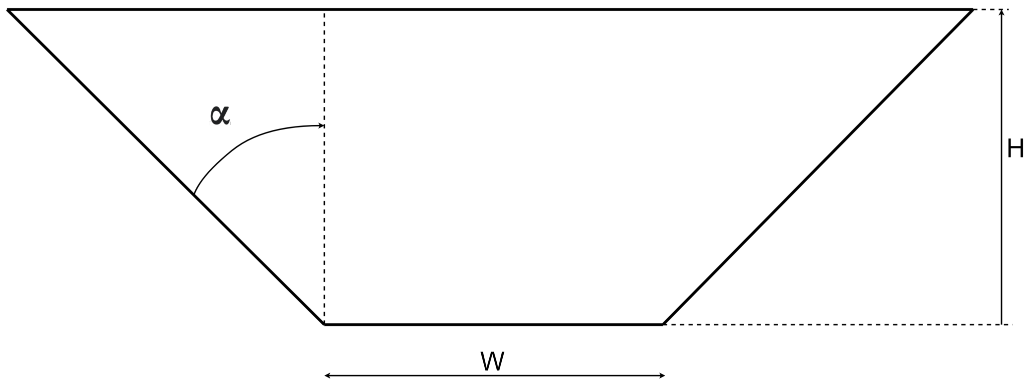

Figure 22: Cross Section of excavated trench. W = {0.96 (PE-RT), 1.11 (Steel)} [m], H = 1.43 [m] and α = 45 °.

6.6.2 Installation of Pipes

In an LCA perspective, the installation procedure consist of lowering the product system components into the shaft and joining them together.

A truck with a mounted crane is used to lower the pipes into the trench. The PE-RT pipe is delivered in a rolled up format and in order to guide it into the trench a cylinder shaped object is put through the middle of the pipe roll, then connected to the crane amd lifted into the air. Through this contraption the pipe and cylinder combinations can rotate freely in the air and then be pulled out either through manual labour or using the excavator. The steel pipes are lowered one by one into the trench as the welding operations progress. While the two products behave very differently in this context, the workers at the construction site believe that, as far as using the truck with the crane, both alternatives are equally time consuming. Having measured the time, it is determined that 100 meters of pipe can be put in place during 1 hour of work. The fuel consumption of the crane and lorry is approximately 4 liters per hour.

The steel product system needs to be welded at the intersection between units. For this application gas welding is utilised. A 3500 °C flame is furnished by a mixture of acetylene gas and oxygen, both compressed and stored in separate tanks. A filler material is melted in the slit, creating the seam. By interviewing welders involved in the project and performing additional calculations, it was concluded that approximately 2.8 liters compressed acetylene and 2.9 liters compressed oxygen was consumed per welded meter.

One of the major practical advantages of the PE-RT product line is the connection procedure which does not require any welding. Instead, the pipes are connected via brass couplings that are attached using a handheld and application specific tool. Its energy consumption is deemed insignificant to the overall scope of the project. The procedure is displayed in video format on the Logstor website [27] (FX-joint installation). As explained in section 6.1.1, a dedicated t-joint made from the same PE-RT material as the main pipe does not yet exist. Consequently, a t-joint from the same product line as the one in the steel scenario but with a larger dimension is used. This implies a couple of unavoidable welding operations to be carried out during the PE-RT system installation.

Having connected the series carrier pipes that constitute each system, the SX-WP joints and the B2S reductions are strapped onto and over the empty space around the junctions. The content in the two pouches in the foam packs are subjected to each other and allowed to react while simultaneously inserting the mixture into the cavity inside the SX-WP and B2S units. These processes are performed manually and do not contribute the collected LCI data. The SX-WP installation procedure is explained in video format on the Logstor website [27] (SX-WP joint installation).

6.6.3 Refilling of Trench

Depending on the situation, the trench can be restored to a seemingly "natural" state where the surface layer is made from the earlier excavated soil or it can be prepared as a load bearing structure, topped of with asphalt. In this report the first case is considered even though it may not represent the actual outcome at Skymningen in the very end.

As shown in figure 23, the trench is refilled with both purchased aggregate (gravel, macadam etc.), so called backfill and part of the previously excavated masses, which here goes by the name of subgrade backfill. The pipe bed together with the surrounding backfill provides structural support to the installed pipe system. The acquired material has a pellet size in the range between 0 to 4 millimeters and, as proposed by one retailer, a density of 1600 kg/m3. Given the calculated trench layer volumes, it is determined that 157 and 186 tonnes of gravel is required to fill the pipe bed and the remaining backfill volume in the PE-RT and steel scenario respectively. Presuming the same type of tipper truck as before, the total amount of trips back and forth from the vendor become 8 in the PE-RT case and 9 in the steel case. Based on internal sources, it can be assumed that the point of purchase is located in Sjöbo, Sweden, implying a one way distance of roughly 40 kilometers. The retrieval of the deposited excavated masses at Hofterup, meant to become subgrade backfill, correspond to 24 trips (PE-RT) and 27 trips (Steel). The production of aggregates, more specifically the energy consumption, is modeled according to a report from IVL - *the Swedish Environmental Research Institute* [47] but has been updated with the emission profiles for diesel and Swedish electricity mix used in this report. The actual process of refilling the trench is accomplished by an excavator and assumed to require the same time and fuel as the actual excavation procedure.

At Skymningen, the ground is actually meant to be covered by asphalt which implies a different composition of layers than what is displayed in figure 23 as well as an additional set of activities. Ultimately it was omitted due to time constraints and the fact that asphalt alone is not crucial to the function of the DH branch.

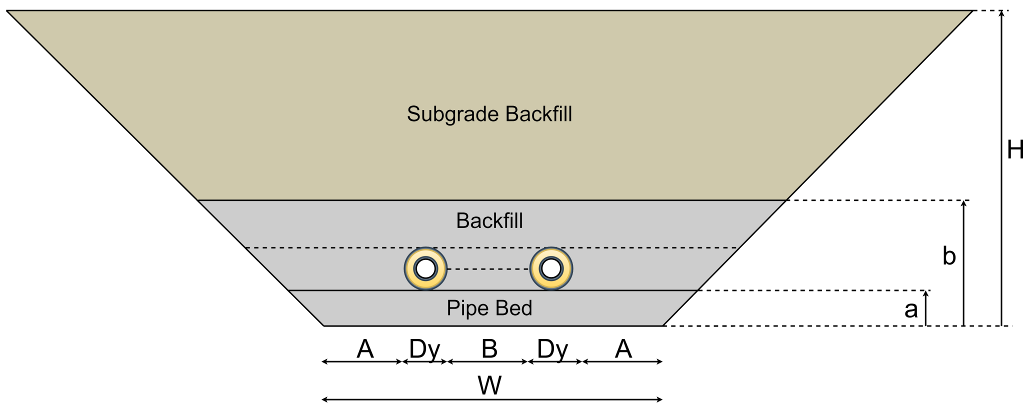

Figure 23: Cross Section of refilled trench.

Table 16: Trench and layer dimensions in meters.

	W	A	B	Dy	H	a	b
PE-RT	0.96	0.2	0.2	0.18	1.43	0.15	0.53
Steel	1.11	0.2	0.35	0.18	1.43	0.15	0.53

6.6.4 Summary: Installation

Table 17: Summation of activities and their respective consumptions.

Activity	Unit	PE-RT	Steel
Excavation			
Excavation	hours [a]	10	11
Waste Removal	trips	32	36
Pipe Installation			
Lowering of Pipes	hours	2	2
Welding	Welding Operations	6	56
Restoration			
Refilling	hours [a]	10	11
Waste Retrieval	trips	24	27
Shipment of Aggregates	trips	8	9

[a] Number of hours required to excavate or refill the considered trench of 115.6 m (PE-RT) / 123.2 m (Steel)

Table 18: Summation of the emissions related to the activities during the installation phase. The emissions carbon dioxide CO_2, sulfur dioxide SO_2 and nitrous oxides NO_x are measured in kilograms.

	PE-RT			Steel		
	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x
Excavation						
Excavation	327	0.16	5.01	360	0.17	5.51
Waste Removal	1 080	<0.01	0.66	1 217	<0.01	0.75
Pipe Installation						
Lowering of Pipes	32	0.02	0.50	35	0.02	0.54
Welding	1	<0.01	<0.01	10	0.02	0.01
Restoration						
Refilling	327	0.16	5.01	360	0.17	5.51
Waste Retrieval	830	<0.01	0.51	936	<0.01	0.58
Gravel Production	221	0.11	3.26	244	0.12	3.61
Gravel Shipment	497	<0.01	0.31	560	<0.01	0.34
Total	**3 315**	**0.45**	**15.26**	**3 722**	**0.50**	**16.85**

6.7 Usage

During the use phase, the pipes act as passive products, not requiring any influx of material or energy to fulfill their duty and the functional unit. District heating water flowing through the system is not destined for the pipes but for the buildings connected to the grid. The emissions attributed to the production of the heat supplied to the facilities are therefore not included in the life cycle of the considered systems. However, there is always an unavoidable heat loss in DH pipes that must be assigned to them specifically. As a consequence, heat production has to be increased to cover the dissipated energy which in turn generates more emissions. The low-T network at Brunnshög is in reality supplied with waste heat from the two research facilities MAX IV and ESS located in the north-western end of the area. The use of waste heat is generally considered climate neutral [48]. The scenario at Brunsshög is quite unique and can not be said to represent a general district heating network. Additionally, by excluding the effects caused by the generation of heat, a vital aspect of the comparison of plastic and steel DH pipe systems in an LCA perspective would be lost. The choice is therefore made to suppose that the Low-T network is connected to and supplied by the powerplant *Örtoftaverket*, which is the primary production unit in the main DH network managed by Kraftringen. A total production efficiency of 100 percent, when including the flue-gas condensation process, is declared by Kraftringen in a brochure describing the power plant [49]. No losses are assumed to occur between the production unit to the entry point of the pipes system.

To calculate the heat loss over the studied lifetime of 30 years, the online program *Logstor Calculator* is used. It is a tool developed by Logstor as a way for clients to analyse pipe system performances by applying system specific parameter values. As input, the following data were applied:

- **Winter**: Supply temperature; 65°C, Return temperature; 35°C, Ambient ground temperature; 8°C, Period; 180 days.
- **Summer**: Supply temperature; 65°C, Return temperature; 38°C, Ambient ground temperature; 12°C, Period; 180 days.
- **Soil cover**; 1000 mm
- **Thermal conductivity soil**: λ_{soil} = 1.6 W/m K
- **PE-RT Pipe System**: PexFlextra, Insulation series 1, d1=110, length=123 m, C=350 mm.
- **Steel Pipe System**: Steel Conti, Insulation series 2, d1=80, length=116 m, C=200 mm.

Along with some other system specific input, the pipe systems' respective thermal performances are determined and displayed in table 19.

Table 19: Performance of insulation and heat loss associated with DH pipe systems.

	λ [W/m K]	W/m (Winter)	W/m (Summer)	**MWh/year**
PE-RT	0.022	22.85	21.59	22.22
Steel	0.023	16.03	15.07	16.53

The larger heat losses associated with the PE-RT pipe system can be attributed to the smaller thickness of the PUR foam compared to the steel system's counterpart.

An interpretation or modelling choice crucial to the end result of the inventory is the decision whether to recognize carbon dioxide equivalent emissions from the combustion of biogenic fuels as contributors to the impact category climate change. In the Swedish energy industry the standard and agreed upon approach is to only report and consider emissions from fossil fuels when externally communicating outside one's organisation. The reasoning being that biofuels are renewable and that their associated emissions are continuously bound in new biomass, effectively creating a closed and sustainable cycle [50]. The ALCA constituting the main body of this report follows this reasoning but the total emissions including the ones from combustion of biogenic fuels are examined in the parameter analysis, i.e. section 8.

In summary, the use phase includes the contributions from the production, transportation and combustion of fossil and biogenic fuels with the large exception of carbon dioxide emitted during the combustion of biofuels. This is further explained in section 6.8.1. When applied to the examined product systems, the LCI data in table 20 is obtained.

Table 20: A summary of the emissions related to the use phase. The emissions carbon dioxide CO_2, sulfur dioxide SO_2 and nitrous oxides NO_x are measured in kilograms.

	PE-RT			Steel		
	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x
Combustion	3 448	17.73	23.35	2 565	13.19	17.37
Transportation	1 352	<0.01	0.83	1 006	<0.01	0.62
Production	1 629	1.13	8.48	1 212	0.84	6.31
Total	**6 429**	**18.86**	**32.66**	**4 783**	**14.03**	**24.30**

6.8 Energy

This section does not represent a specific inventory phase but acts as a summary of energy sources and carriers present in various parts of the main ALCA. In other words, the emissions related to energy consumption for each phase is already included in the previous LCI tables but their backgrounds are explained here. The "emissions per unit energy" for each energy carrier is presented in table 22.

6.8.1 Kraftringen District Heating Production

Kraftringen's main district heating network provides the municipalities Lund, Lomma and Eslöv along with the area Dalby with heat. The central production unit is Örtoftaverket, a combined power and heat plant with an approximate annual production of 500 GWh of heat and 220 GWh of electricity [49]. The steady state fuel mix is made up of one hundred percent solid biofuels, of which roughly 55 percent is constituted by recycle waste wood (RWW) and the remaining 45 percent by primary/secondary forest fuels. During the period 2013 until 2018, Peat accounted for approximately fifteen percent of processed fuel but has since then been excluded from the fuel inventory. The starting sequence of the furnace is powered by oil, comprising the only fossil input to the power and heat generation. As of the summer of 2020, the fossil oil has been replaced by HVO, a renewable and biogenic type of diesel. This is not taken into account in the report since company-specific data describing the HVO's associated emissions has yet to be produced. As mentioned previously, the power plant has a total efficiency of one hundred percent. With these things taken into consideration, data exclusive to the year 2018 are included in the model since they are the most recent and that previous years are not representative of the current situation.

Due to its nature as a facility that produces both electricity and heat, the relative impact of each energy carrier has to be decided through allocation. Common practise is to utilise a method known as *the Alternative Production Method* (originally "Alternativproduktionsmetoden" in Swedish). Through the knowledge of total heat and electricity production as well as type of fuel, it provides a percentage of the total emissions that should be attributed to the heat and power generation respectively. For the main ALCA scenario, heat production carries 51 percent of the total emission output. An explanation of the method is available in the appendix.

It should be heavily emphasized that the carbon dioxide emissions from the combustion processes presented in this section only represent the contribution from the fossil fuel (oil) input. This means that for the entire energy production from a power plant during a given time period, only the carbon dioxide emissions from fossil fuels are accounted for, even though they make up a small fraction of the total fuel input. On the other hand, the other types of emissions, such as SO_2 and NO_x are not "discriminated" against, i.e. one does not differentiate between fossil or biogenic fuel sources.

Besides combustion, the production and transportation of the fuels are also relevant to the study. The shipment of fuels are made by truck and around 30-35 deliveries of biofuel are received each day. Shipments of oil occur 5 times a year. The transportation activity and the trucks are modelled as in section 6.3. As explained in section 6.6.1, every shipment is dedicated to the delivery of biofuel, eliminating the need for an allocation procedure but forcing the inclusion of the effects from the return trip. The production of biofuels is more complicated to define and condense into something strictly applicable to the studied system. There main problem is to define the system boundaries and solve allocation problems related to the forest management, harvesting and fuel processing. As a solution, secondary data from the EF database representing sustainable forestry and biofuel production in Sweden an Finland was utilized.

Table 29 displays pertinent properties of the three fuel types as well as information regarding the deliveries of the fuels. The information is provided by internal sources at Kraftringen except for the kg $CO_{2,eq}$/MWh which is provided by Energiföretagen [48]. The latter includes emissions from production and transportation, and in the case of the oil, also combustion. It is only meant as a way to give the reader an idea of the differences in emission output between the fuels and more accurate values provided by Kraftringen are used in the actual system model.

Table 21: Fuel characteristics and delivery data.

	Properties		Delivery		
	MWh/t	kg $CO_{2,eq}$/MWh	t/year	Distance [km]	Deliveries/year
Forest Fuel	2.8	268	114 300	86	11 900
RWW	3.7	4	93 200	86	11 900
Heating Oil	11.9	4	200	250	5

6.8.2 Swedish Electricity Mix

The emission data representing the Swedish electricity mix are based on two separate sources. Wind, solar, hydro and nuclear power production are modeled according to the EF database [39] while the characteristics of electricity originating from combustion is taken from statistics provided by Energiföretagen [51]. Information about the total amount of electricity added to the grid from each energy source comes from the international energy agency (IEA) website [52]. Sweden's domestically produced electricity mix is made up of 57 percent renewable energy sources [51]. In the context of emissions, this can be somewhat misleading since nuclear, one of the two major means of electricity production and with a low carbon intensity, is not considered renewable. If that would have been the case, the amount would be closer to 98 percent.

6.8.3 Danish Electricity Mix

The emissions levels attributed to the Danish electricity grid mix are based on data from Energinet [53], a independent public enterprise part of the Danish ministry of climate, energy and supply. The data only considers domestic electricity production. Information about the total amount of electricity added to the grid from each energy source comes from the international energy agency (IEA) website [52]. The Danish mix is largely supplied by renewable resources, approximately 60 percent [54]. As an indication of the environmental performance of the national production, the grid mix has a carbon dioxide intensity of around 200 g $CO_{2,eq}$/kWh produced [53].

6.8.4 Diesel

For heavy-duty vehicles (large trucks, excavators etc), the diesel engine is the most common choice due to its advantages in torque and fuel efficiency compared with its petrol equivalent [43]. In this report, fossil diesel is considered which is produced through the distillation of crude oil. The data used for modelling the impact of diesel production and diesel combustion present in the studied system comes from the EF database [39]. Even tough the largest consumption of diesel in the two examined life cycles are located in the transportation activities, their emissions are registered as a function of per-kilometer-traveled, effectively accounting for but at the same time masking the impact of the diesel consumed. As such, the diesel data discussed in this section is exclusive to the installation life cycle phase, more specifically the construction machines. The EF database provides values for $kg_{emission}/kg_{diesel}$ and in order to convert it to $mg_{emission}$/MJ, data from Preem [55] and the Swedish Energy Agency [56] were used.

6.8.5 Summary Energy

Table 22: A summary of the emissions of for each considered energy source and carrier discussed in section 6.8. Values are given as mg/kWh or mg/MJ. DHH = District Heating Heat, SEM = Swedish Electricity Mix, DEM = Danish Electricity Mix.

	CO_2	SO_2	NO_x	CO	N_2O	CH_4	NH_3	NMVOC	$PM_{2.5-10}$
DHH [a]	9 644	28	49	41	2	20	<1	9	<1
SEM	9 730	11	13	10	<1	6	<1	2	4
DEM	185 040	26	21	140	3	110	-	22	14
Diesel [b]	78 620	38	1 212	380	2	96	5	130	83

[a] Represents production, transportation and combustion of oil and biofuels with the exception of biogenic carbon dioxide from the combustion process.
[b] Measured in mg/MJ

6.9 Final Inventory

Table 23 presents a summary of the previous LCI tables in the inventory.

Table 23: A summary of the emissions of each life cycle phase. The emissions carbon dioxide CO_2, sulfur dioxide SO_2 and nitrous oxides NO_x are measured in kilograms.

	PE-RT			**Steel**		
	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x
Extraction and Refinement	3 925	7.40	7.71	5 917	11.50	10.23
Transport to Logstor	74	«0.01	0.05	114	«0.01	0.07
Manufacturing	132	0.03	0.15	88	0.04	0.11
Transport to Lund	49	«0.01	0.03	66	«0.01	0.04
Installation	3 315	0.45	15.26	3 722	0.50	16.85
Usage	6 429	18.86	32.66	4 783	14.03	24.30
Total	**13 924**	**26.74**	**55.86**	**14 690**	**26.07**	**51.60**

7 Environmental Impact Assessment

This section is what in many technical reports would be called "Results". The two first questions in the research questions are answered here while the last is answered in the parameter analysis. The LCI data collected in the inventory is translated, grouped and presented in the form of reference unit equivalents for each considered impact category. With the intention of a more perspicuous result section, resource extraction and processing has been merged with manufacturing at Logstor under the name *Manufacturing*. This applies to the two transport phases as well, presented under the common banner *Transportation*.

The environmental impact assessment method deployed, *Product Environmental Footprint*, proposes the following impact factors for some of the most common and important types of emissions. As laid out in the theory, it can be explained according to the following example. Nitrous oxide has an impact factor of 298 in the GWP category. This means that for one kilogram of released N_2O, the addition to the driving forces behind climate change equal those of 298 kilograms of released carbon dioxide which is the reference unit with a factor 1.

Table 24: Characterisation Factors for some important emission types.

	Unit	CO_2	SO_2	NO_x	CO	N_2O	CH_4	NH_3	NMVOC
AP	mol H^+_{eq}/kg	-	1.31	0.74	-	-	-	3.02	-
EP	kg N_{eq}/kg	-	-	0.389	-	-	-	0.092	-
GWP	kg $CO_{2,eq}$/kg	1.0	-	-	1.57	298	36.8	-	-
POCP	kg $NMVOC_{eq}$/kg	-	0.0811	1.0	0.0456	-	0.0101	-	1.0

Figure 24 portrays the final comparison between the PE-RT and Steel systems. The result is in percent where the option with the largest impact is assigned 100 percent and the the other is scaled relative to the first. It should be kept in mind that the results from the different impact categories are not comparable. PE-RT has a larger aggregated impact in the AP, EP and POCP categories but end up being the better option as for GWP. The following graphs (figures 25 through 28) are given in absolute numbers. Generally speaking, the use phase is the largest contributor in every impact category, followed by manufacturing, installation and transportation in that order. The large exception to that rule are the $CO_{2,eq}$ emissions from the manufacturing phase, almost mirroring those of the use phase.

Regarding the areas with a significant contribution, also know as hotspots, manufacturing and the use phase are, with a few exceptions, the reoccurring "champions" no matter the impact category. Dissecting the systems a bit further, the combustion of fossil fuels for the sake of heat generation is the largest emission source for both systems and in every impact category. The sole exception is the production of steel and steel pipes whose output marginally surpasses the effects of those of heat production in the steel case. Other processes with an considerable impact include biofuel production, transportation of biofuels and excavated masses, production of PUR foam constituents and in the PE-RT case, the fabrication of polyethylene granulate.

The effects of *Transportation* are not equal to zero for AP, EP and POCP but they are really small compared to the releases from the other life cycle phases.

Table 25: The final LCIA data displaying the impact of each life cycle phase on the selected impact categories.

	AP [mol H^+_{eq}]	**EP** [kg N_{eq}]	**GWP** [kg $CO_{2,eq}$]	**POCP** [kg $NMVOC_{eq}$]
PE-RT				
Manufacturing	16.5	3.7	5 066	14.1
Transportation	0.1	<0.05	124	0.1
Installation	12.1	6.1	3 383	17.3
Usage	50.0	13.1	7 436	43.0
Total	**78.7**	**22.9**	**16 009**	**74.5**
Steel				
Manufacturing	23.7	4.5	7 263	16.9
Transportation	0.1	<0.05	181	0.1
Installation	13.4	6.7	3 796	19.1
Usage	37.2	9.7	5 532	32.0
Total	**74.4**	**20.9**	**16 772**	**68.1**

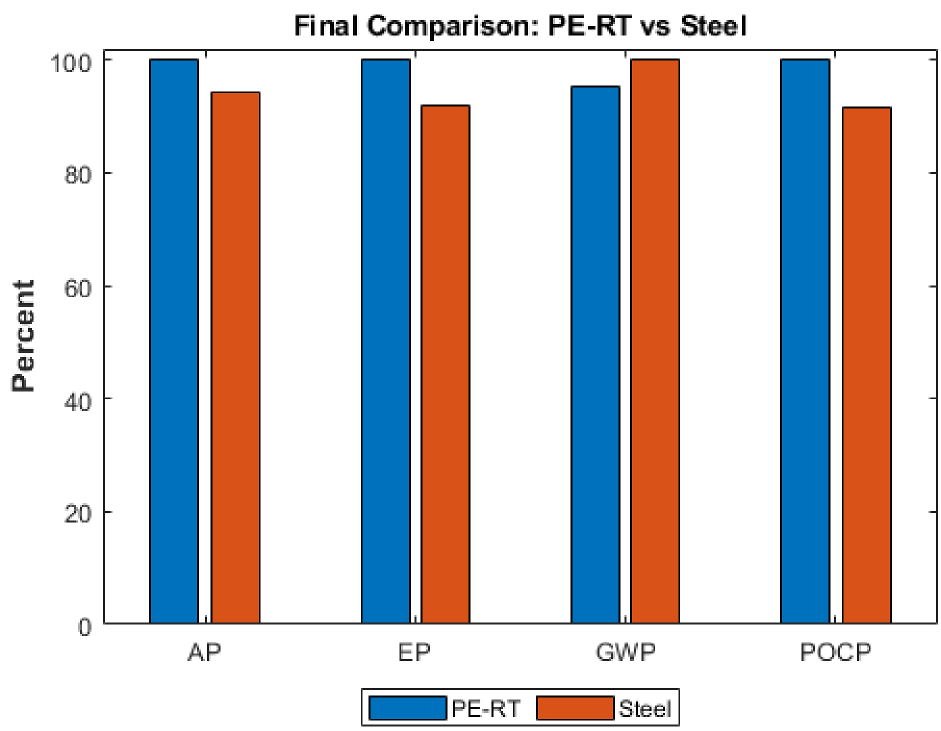

Figure 24: The final and complete comparison of the PE-RT and Steel product systems for each considered impact category.

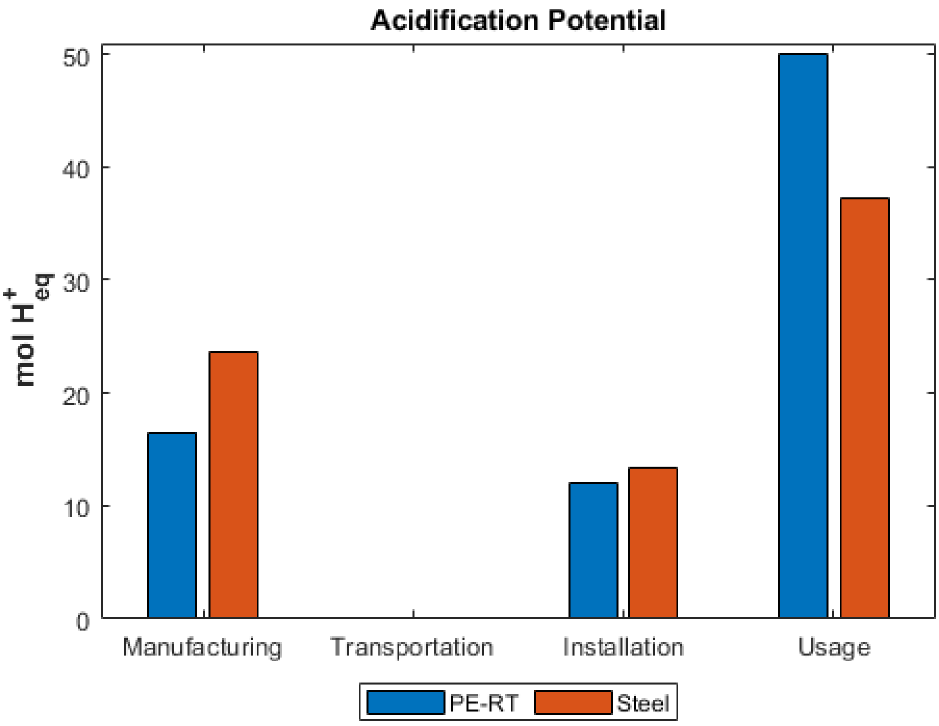

Figure 25: Contributions to AP divided per life cycle phase and product system.

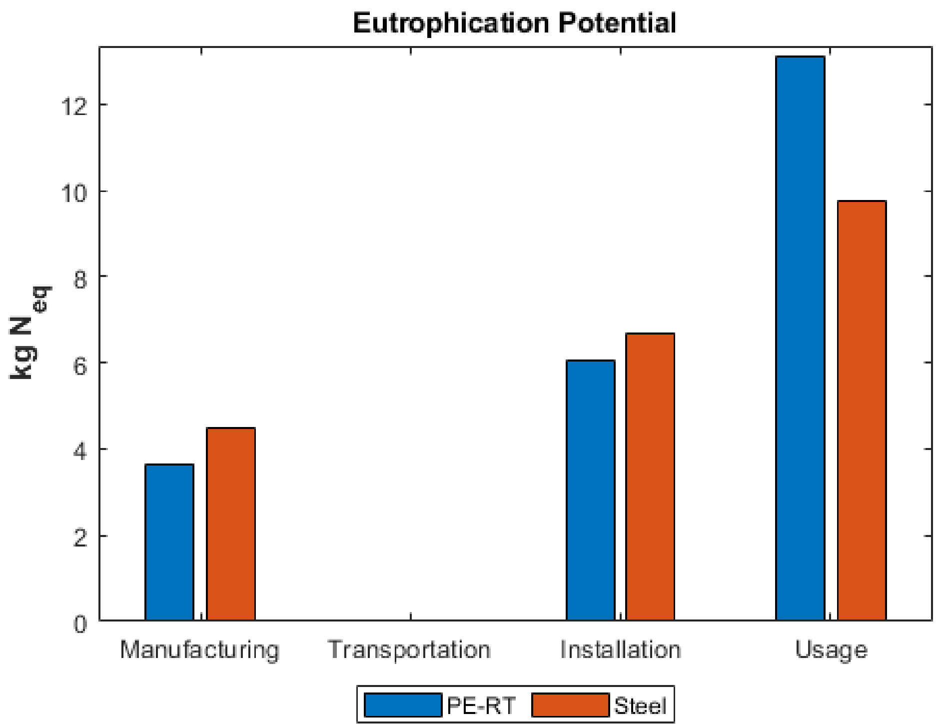

Figure 26: Contributions to EP divided per life cycle phase and product system.

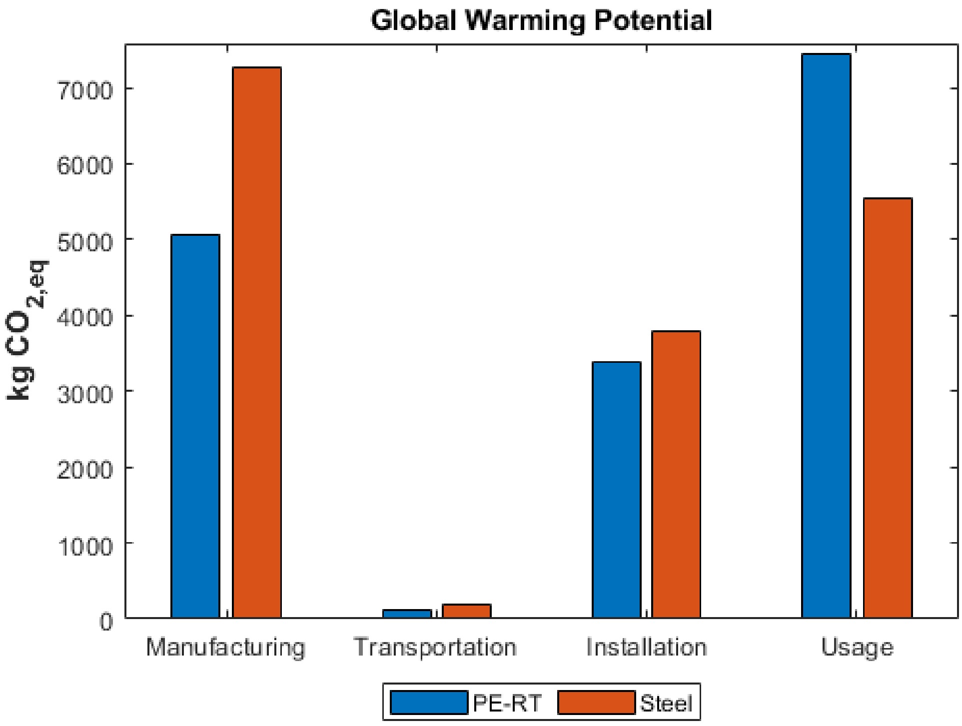

Figure 27: Contributions to GWP divided per life cycle phase and product system.

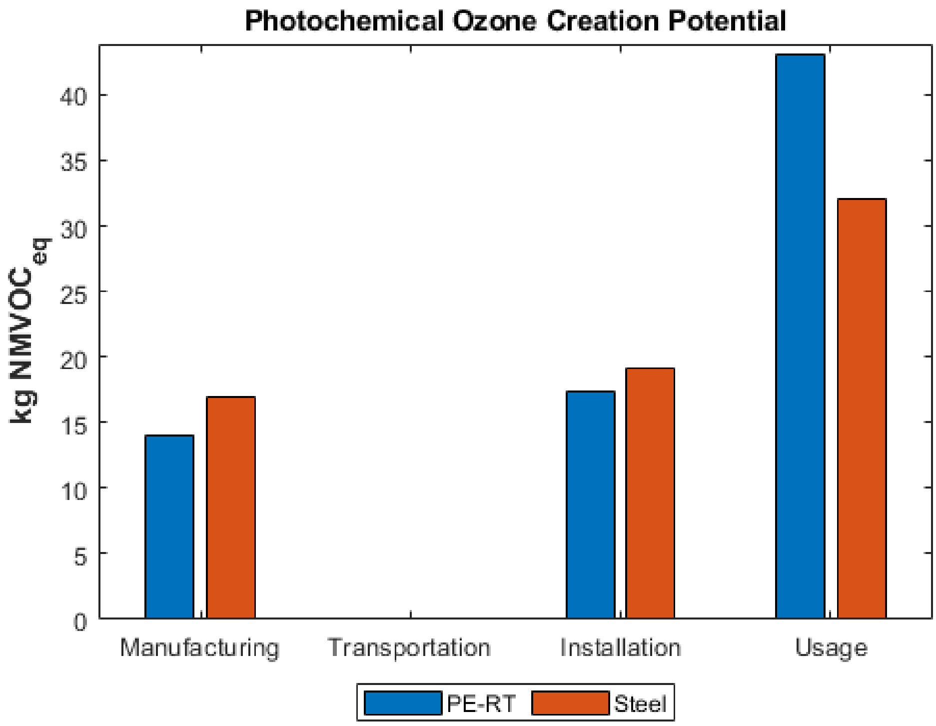

Figure 28: Contributions to POCP divided per life cycle phase and product system.

8 Parameter Analysis

As a way to further one's general understanding of the studied system it is important to be able to relate it to external factors and/or alternative life cycle configurations. The parameter analysis aims to divulge differences in the output of a system and to evaluate its robustness when adjusting model variables and/or system boundaries. In this report the chosen topics relate to different interpretations of biogenic emissions, alternative steel and PE origins as well as dimensional and temporal parameters related to the district heating pipe products. Each case is treated as a separate entity and is only related to the main ALCA but not part of it. In other words, the parameter studies do not add on top of each other.

8.1 Inclusion of Biogenic Emission from Heat Production

This section explores the implications of two opposing approaches related to emissions produced by the combustion of biofuels. It should be kept in mind that its connection to the study solely can be attributed to the heat losses present in the two product systems during the use phase. The arguments and points expressed in following segment aim only to validate the existence of this particular parameter study and is not intended as a debate on energy policies.

As mentioned previously in section 6.7, common practice in the energy industry is to view the conversion of biofuels into heat and electricity as a carbon-neutral process. The underlying idea is that carbon released to the atmosphere from the combustion of biomass will be absorbed by new, growing biomass which in turn can be turned into fuel, effectively creating a closed system that does not contribute additionally to anthropogenic climate change. This approach is adapted by industry associations and state departments throughout Europe and can be traced back to the EU Renewable Energy Directive [57] in which it states that *"- Emissions of the fuel in use, e_u, shall be taken to be zero for biofuels and bioliquids"* (Annex V, point 13). e_u refers to a variable representing the emissions of biofuels and bioliquids in an equation used in the same document. It should be emphasized that this only concerns the combustion of biomass and that production and transportation of the fuel are not assumed to be zero-value parameters.

This decision is however contested by parts of the scientific community. Multiple sources [57], [58], [59] claim that the adapted policy fails to recognize that land that could be used for biofuel production normally already hosts biological ecosystems such as forests. The existing plants would already be sequestring carbon from the air, resulting in a sort of double-counting where bioenergy is credited for reducing atmospheric carbon through plant growth. Furthermore, problems related to indirect land-use change (ILUC) are not accounted for under the discussed policy. According to the referenced reports, an incorrect application of the UNFCCC (United Nations Framework Convention on Climate Change) treaty allows for the assumption of bioenergy's carbon-neutrality. This created the possibility, in certain contexts, of allocating emissions related to biomass to the category *land-use* rather than to the category *energy*. This is not in itself the actual problem since as long as the emissions are accounted for somewhere the total carbon dioxide net flux remains correct. However, if only examined through the scope of energy related policies and treaties, the problem becomes evident. The EU Renewable Energy Directive does mention the importance of minimizing ILUC but in the eyes of the detractors the underlying problem caused by the zero-emission approach still presists. If the opposing arguments are acknowledged to their full extent, then the idea to treat biofuels as carbon-neutral and simultaneously calling for an increased share of renewable biofuels to the overall energy mix could yield long-term negative consequences.

This topic is immensely complicated and it is fair to assume that circumstances vary on national, regional and corporate levels. Through a societal perspective, there are other issues besides the environment, such as the economy and self-sufficiency, that are worthy of consideration. To explain the complete set of aspects and proposed pros and cons of the directive is beyond the scope of this study. However, no matter the current situation, it is not unrealistic to imagine a future scenario were more stringent rules and regulations apply and a reduced leniency towards biofuels exist.

As for Kraftringen and heat/power generation, the two types of biofuels used during stationary production are forest fuel and recycled waste wood. Although not explicitly mentioned in the critical reports, the seemingly largest culprit in the bioenergy ordeal are cultivated plants intended for energy purposes, where previously untouched green areas or forests have been converted for that specific application. An outtake of biomass from a "sustainable forest" or recycled wood material might have a smaller impact than cultivated biomass but can still not be fully exempt from the proposed criticism. The Swedish agency *Naturvårdsverket* gives credence to this claim, referring to the fact that the expansion of the Swedish forest in terms of biomass is larger than the outtake and loss through natural decomposition combined [50].

Since the single difference between the main ALCA study and the case discussed in the section at hand is the inclusion of biogenic carbon dioxide released during combustion, the focus of this particular comparison is altered global warming potential. For the year 2018, the output of carbon dioxide exclusive to the combustion of fossil fuel (oil) was measured to be 5.2 kg/MWh. When including the contribution from biofuels this value becomes 176.6 kg/MWh, an increase of roughly 3 400 percent. Both values are allocated to heat generation. The difference and its effect on the result presented in the environmental impact assessment is displayed in figures 29 and 30. The first is an alteration of figure 27 and the latter is an alteration of figure 24. The enormous implications of this specific factor quickly become apparent. GWP, having had the closest race in the principal comparison, now end up with a more than 20 percent difference between the two product systems.

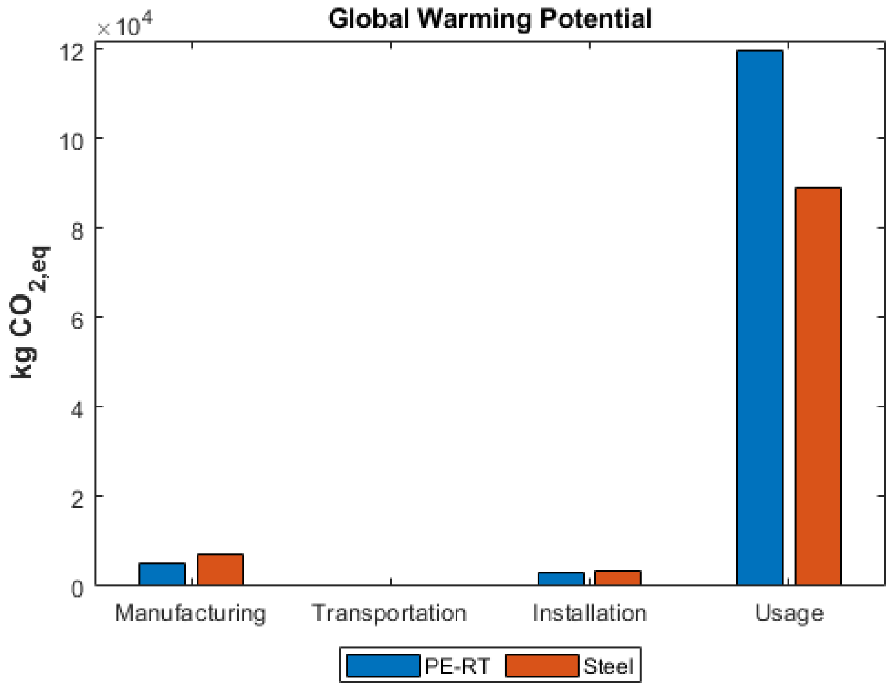

Figure 29: Parameter study: Representation of contributions to GWP divided per life cycle phase and product system when including biogenic carbon dioxide from combustion.

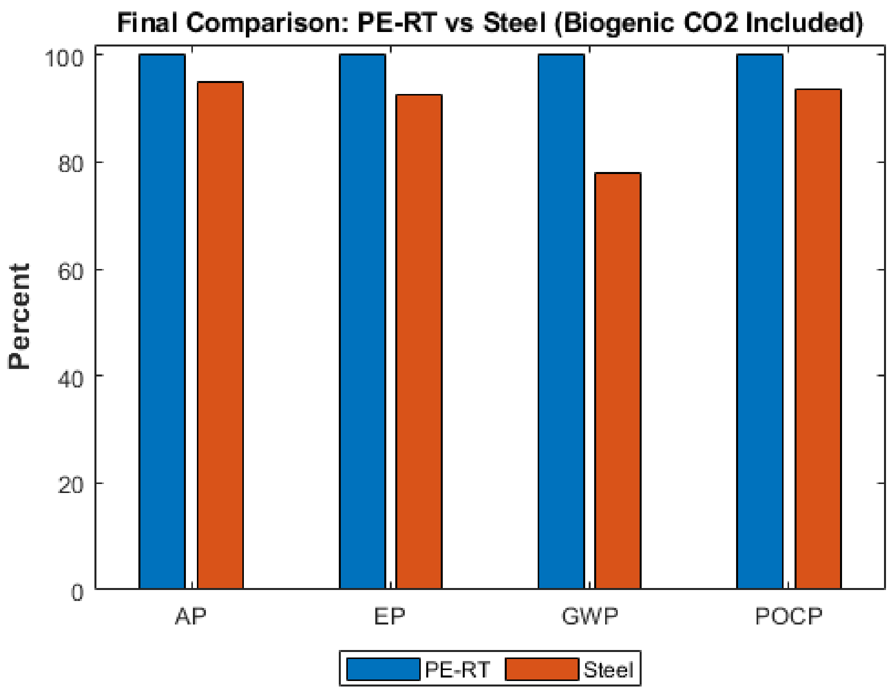

Figure 30: Parameter study: Portrayal of the complete performance of the PE-RT and steel systems in a GWP perspective when including biogenic carbon dioxide from combustion.

8.2 Alternative Steel Origin

This section aims to explain and portray an alternative steel production route meant to act as a basis of comparison in the parameter analysis. The goal is to provide an idea of the differences in environmental impact allocated to each system. Due to lacking data, only carbon dioxide emissions and, by extension, global warming potential are considered.

China is the single largest producer of steel in the world [60]. As of 2018 their domestic steel production was 928.3 megatonnes which was 8.7 times the amount produced by India, second on the list, the same year. The country is also associated with a carbon intensive industry. These factors considered, Chinese steel is deemed a good candidate for the comparison with European steel.

There are several applicable sources analysing the CO_2 emissions related to steel manufacturing in China. One major problem arising when comparing source material from different countries and institutions is the lack of a common methodology. Industry representatives and scientists in one part of the world might use certain assumptions, approaches to calculations and system boundaries. Trying to compare data from China with a seemingly corresponding dataset from Europe may therefore yield inconclusive results. Therefore, a report comparing the CO_2 intensity of the steel industry in China, Germany, Mexico and the US [61] during the year 2010 is selected as the main source for this section. The benefit of using a report investigating both geographical locations at once, is the level of conformity between the results of the different scenarios. Consequently, the analysis presented in this section compares the Chinese scenario with the German scenario (acting as an European average) from the considered report as well as with the main ACLA scenario examined in this study. Only the cradle to gate production of steel and the shipment to Logstor are included in the parameter analysis.

According to the report, the production of crude steel in China during 2010 accumulated to 638.74 megatonnes and the CO_2 intensity was approximately 2150 kg CO_2 per tonne produced crude steel. Applying the latter metric to the case specific steel quantities generate a total of 3616 kg CO_2 per functional unit.

Overlooking the previously mentioned inconsistencies related to reporting and calculations, there are two major contributing factors to the disparity between domestic steel production emissions in China and Germany. The first one is the use ratio of electric arc furnaces (EAF) to blast furnaces (BF) and or basic oxygen furnaces (BOF) where the latter ones are processes with a larger carbon intensity. Added to this is the Chinese industry's predisposition towards the usage of the highly carbon intensive pig iron as feed material to the EAFs. The second reason is the electricity grid mix which in China, compared to the European average, has a higher percentage of fossil fuels as primary energy input.

Another aspect to the Chinese steel route is the change in geographical position and its implications on the shipment of goods to Logstor. From China to Europe the main transportation method and route is by boat through the Suez canal [62]. For this instance it was assumed that the shipment route started in Shanghai, China, and ended in Bremen, Germany, a distance corresponding to roughly 20400 kilometers [63]. The remaining distance from Bremen to Logstor, Denmark is modeled the same way as in section 6.3. The emissions related to the maritime shipping are here based on an alternative approach to transportation calculations in which the unit kg*km is used. By knowing the emissions for 1 [kg*km], the idea is then to multiply the weight of the transported goods with the distance covered as a way to scale and conform the numbers to the case at hand. However, this method is somewhat inaccurate and works well for approximations as stated by the employees at Green Delta themselves [64]. The production of and starting point for the German steel is assumed to be the region of North Rhine-Westphalia, which allegedly is the state that produces the most steel in Germany [65].

Instead of using geography as the baseline for a comparison, one could also examine different means of production. Currently, a lot of attention is being given to the incorporation of hydrogen as a reductive agent in the steelmaking process. As explained in an article by researchers at Lund University [66], hydrogen could be used to turn iron ore pellets into a substance known as sponge iron which in turn could be fed into an electric arc furnace to produce steel. This would cut out the very energy and emission intensive blast furnace and basic oxygen furnace from the refinement line. Further, if the proposed solution were to be coupled with hydrogen supplied from an electrolysis process powered by renewable electricity then steelmaking could potentially reduce its emissions of carbon dioxide up to as much as 97 percent. The Swedish steel producer SSAB, together with the mining company LKAB and the energy company Vattenfall are currently on the road to implement such a solution with the construction of a pilot plant in Luleå, Sweden. Since the first few years of the venture will be focused on testing, actual production volumes will not hit the market until 2026. Actual logged data from the steady state operations do not yet exist and therefore this alternative steel route is not considered in the parameter analysis.

Table 26 displays the total emissions of CO_2 to the atmosphere from the production and transportation of steel equivalent to the amount required to fulfill the functional unit in the main ALCA. The Chinese and German cases discussed above are considered and are presented alongside the corresponding emissions from the main ALCA case (denoted as "Base Case") as a way to highlight the inherent problems of comparing data from different institutions and parts of the world.

Table 26: Parameter study: Total emissions in kg CO_2 for Chinese and German steel as well as the output from the main ALCA as a reference case.

	Production: kg CO_2	Transportation: kg CO_2
Chinese Steel	3616	111
German Steel	2842	45
Base Case	4482	85

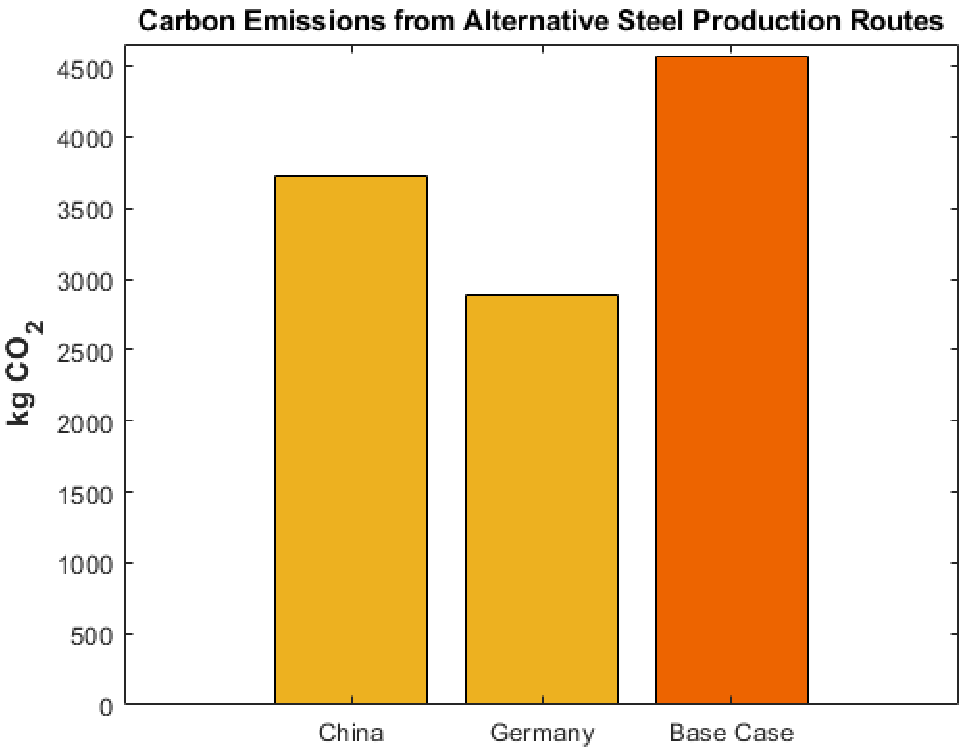

Figure 31: Parameter study: Carbon dioxide emissions from three different routes associated with extraction, production and transportation of the amount of steel required to fulfill the functional unit in the main ALCA.

8.3 Alternative Polyethylene Origin

In the main ALCA, all polyethylene products originated from fossil crude oil. An alternative way of acquiring ethylene (represented by the turquoise branch in figure 32) is through the processing of biological feed-stock such as sugarcane. Renewable in nature, the method does not contribute to abiotic resource depletion and might, depending on the situation and feed-stock, actually act as carbon sink. On the other hand the cultivation of biomass implies land use which, once again depending on the situation, can have a heavily reversed effect on several LCIA categories. It is safe to say that the topic of fossil versus renewable feed-stock for PE production is a huge area to cover and most probably more complex and with more expansive ramifications than the main topic of this report. This section can therefore not cover all the intricacies related to the subject but simply summarize the most essential findings in other peoples' works. As mentioned in the section about alternative steel origins, it can be dangerous to incautiously compare information from different geographical and institutional backgrounds. To circumvent this problem, the report *Comparative Life Cycle Assessment of Polyethylene Based on Sugarcane and Crude Oil* by C. Liptow and A. Tillman [67] is used as the sole reference for this segment. The consulted report adopts the midpoint impact assessment method CML (Centrum voor Milieukunde Leiden) which proposes different impact factors for common compounds, preventing a direct translation of LCIA data to fit the, in this report, employed PEF method. Instead, the result displayed in 33 are directly fetched from the referenced study without any adjustments made. The step discussed in the report where the PE is incinerated at the end of its life time to generate energy is however ignored. Furthermore, it should be noted that the CML method also proposes slightly altered impact categories, for example the eutrophication potential is a generic version of the concept while the main ALCA looks at a specifically marine adaptation.

The report examines two scenarios, firstly PE produced from sugarcane in Brazil and secondly PE produced from oil in Saudi Arabia. Both products are transported by boat to Europe. The oil route follows the steps laid out in section 6.2.2. To extract ethylene from sugarcane, the first step is to prepare the land for agricultural activities (not shown in figure 32) which includes sub-soiling, planting seeds and adding fertilizers. When the sugarcane is ready for harvesting it is cut down, washed and crushed to extract the desired juice. A by-product known as bagasse is retrieved which is burned to provide the required energy for the subsequent ethanol production. By adding yeast to a sugar slurry, it metabolites the sugar creating ethanol. The alcohol is then distilled to increase its concentration. Finally, the product is dehydrated which essentially means removing oxygen and some hydrogen from the ethanol (forming water) to obtain ethylene. The polymerisation is the same as for the oil route.

Similar to the two previous parameter analysis sections, the authors of the report do acknowledge the problems of LCI data collection from foreign and distant enterprises and also the dilemma of incorporating the effects of direct and indirect land use. The results presented in figure 33 do not contain the emissions related to land use but the report does provide a value of what that could be which, if applied, would turn the category GWP on its head, cementing the oil route as the more climate-friendly option. An interesting aspect of oil-derived PE not covered in the referenced study is the possibility of using sugar beets, which are cultivated in Europe, as a replacement for the sugar cane route. As a positive consequence, the implications of large shipment distances would be nearly eliminated. As insinuated by [68], the major obstacle suppressing the feasibility of such a solution is the economic competition from sugar cane but mainly oil.

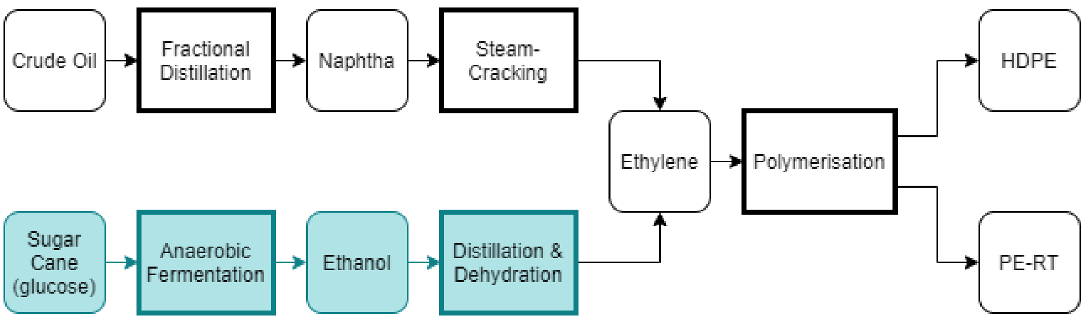

Figure 32: Cradle to gate timeline of PE. Turquoise branch represents the alternative production method of the ethylene.

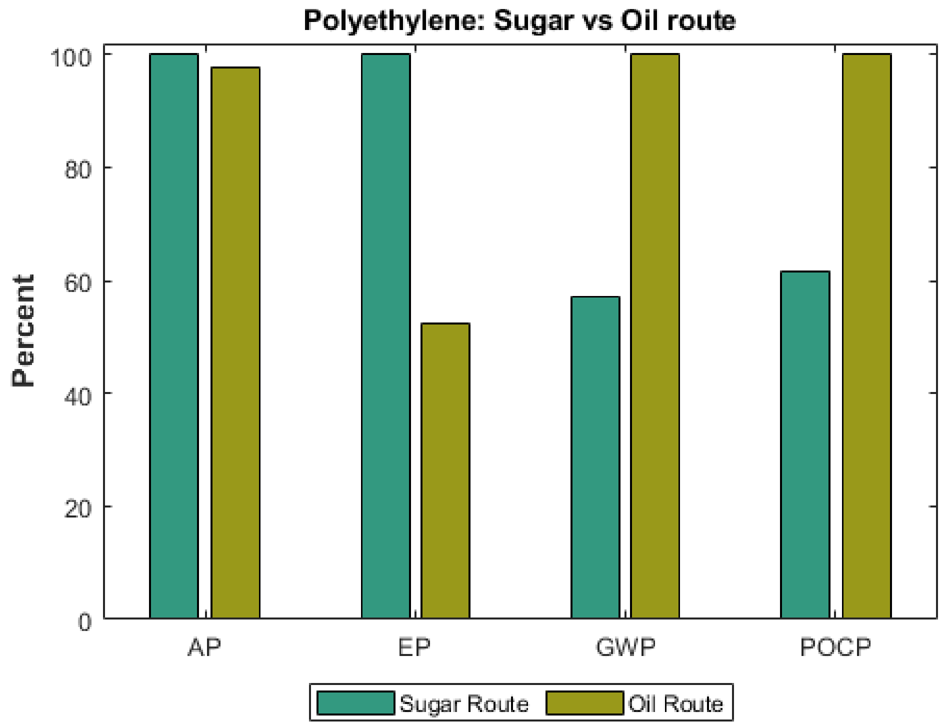

Figure 33: Parameter study: Environmental performance of the sugarcane and oil routes pertaining to the production of polyethylene.

8.4 Heat Loss as a Function of Supply and Ground Temperature

In section 6.7, several inputs to the *Logstor Calculator* program were mentioned, among which ground temperature T_g and supply temperature T_s were part. The given values for the first one were based on data from SMHI and the second one is the current supply temperature of the network. Both are possible subjects of change and/or variability. Since the emissions from the use phase are related to the heat losses occurring in the pipes which in turn are functions of the difference between these two temperatures, they are worthy of further investigation.

The seasons "Summer" and "Winter" are merged and given the average value of 10 °C ground temperature. A reasonable variance of ±3 °C is assumed. As for the supply temperature, the 4th generation of district heating is aiming for 50 °C and reasonably not above 65 °C. The two variables are set to: $T_g = \{7, 13\}$ °C and $T_s = \{50, 65\}$ °C. Inserting every combination of the two variables into the program yields the heat loss values in table **??**. By assuming a locally linear pathway between each set of two points for each system, the heat losses for the PE-RT and steel systems can be mapped as functions of T_g and T_s using Matlab. This is displayed in figure 35

Table 27: Heat losses in MWh/year as a function of supply and ground temperature boundary values.

	PE-RT		Steel	
	T_s = 50 °C	T_s = 65 °C	T_s = 50 °C	T_s = 65 °C
T_g = 7 °C	19.77	23.86	14.70	17.74
T_g = 13 °C	16.49	20.58	12.27	15.31

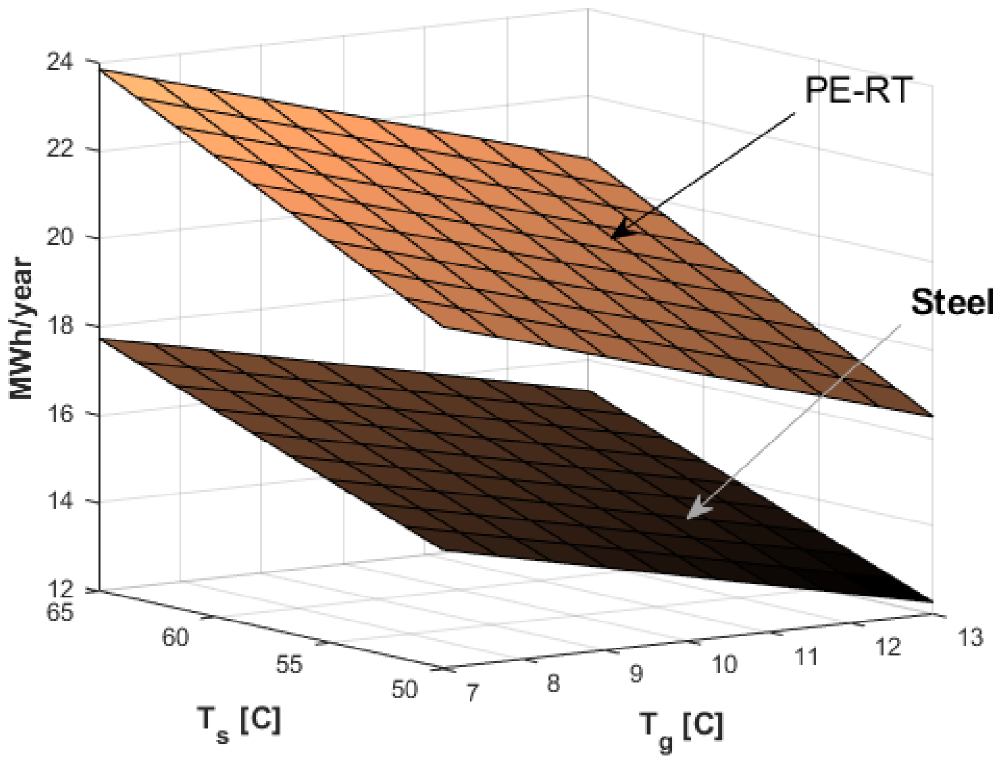

Figure 34: Parameter study: Heat losses [MWh/year] from the PE-RT and steel systems as functions of T_g and T_s [°C].

Finally, this can be related to the amount of emissions released. Figure 35 displays the difference in GWP between the scenario with the lowest heat losses (A), the scenario with the highest heat losses (C) and the one that represents the scenario in the main ALCA (B). Most of the function surface representing the PE-RT system lies above the corresponding one for the steel system. In any case, the only sensible comparison between the two product systems that can be made is by looking at the points with the same pair of T_g and T_s coordinates. As such, the PE-RT system will always have higher heat losses within the given range.

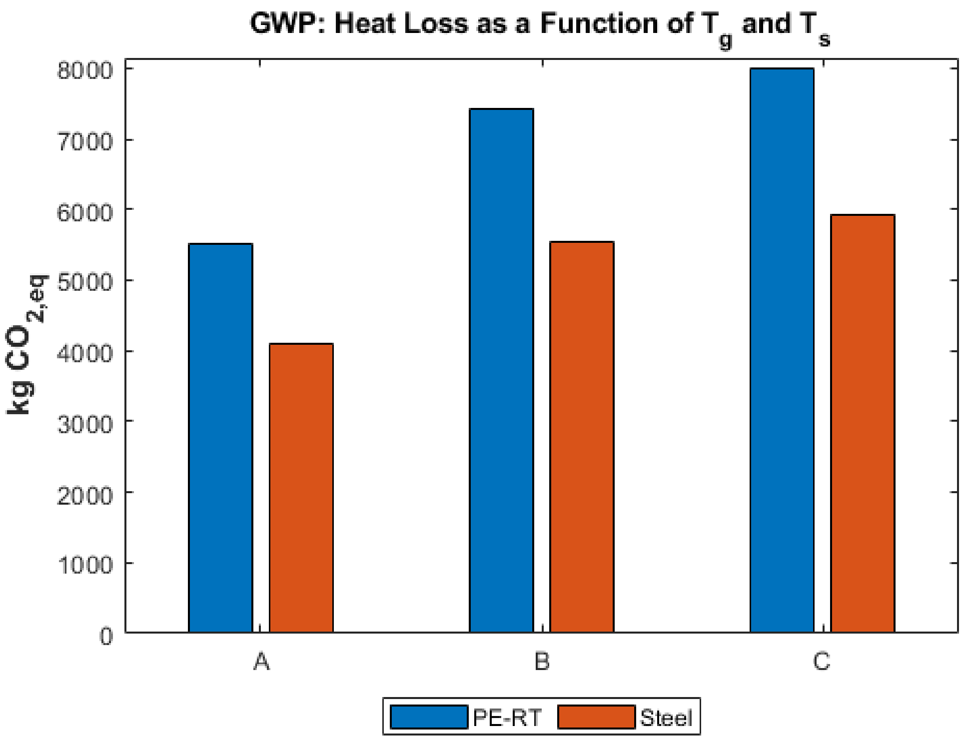

Figure 35: Parameter study: Release of $CO_{2,eq}$ in kg due to heat losses from the PE-RT and steel systems when varying T_g and T_s.

A: T_g = 13 °C , T_s = 50 °C
B: T_g = 10 °C , T_s = 65 °C
C: T_g = 7 °C , T_s = 65 °C

8.5 Increased PUR Foam Thickness in PE-RT DH Pipes

As revealed in the LCIA results, the single most impactful entry in every impact category is the use phase for the PE-RT system, more specifically the emissions associated with the heat losses experienced in the pipes and the other components. As mentioned before, the underlying reason for the difference between the two systems in this regard is the smaller thickness of the PUR foam in the PE-RT system. An interesting question then becomes at what additional PUR foam thickness the PE-RT system achieves the same insulation capacity as the steel version. An alternative approach to solving the problem could be to introduce another blowing agent with better insulating capabilities but this segment focuses solely on the addition of PUR foam. Equation 3.12 in the book *Introduction to Heat Transfer* [69] describes the heat transfer phenomena over a multilayered tube. Adapting it to the given scenario and neglecting external convectional forces yields:

$$\dot{Q} = \frac{t_i - t_o}{(2\pi L\lambda_c)^{-1}\ln(\frac{r_2}{r_1}) + (2\pi L\lambda_i)^{-1}\ln(\frac{r_3}{r_2})} \tag{4}$$

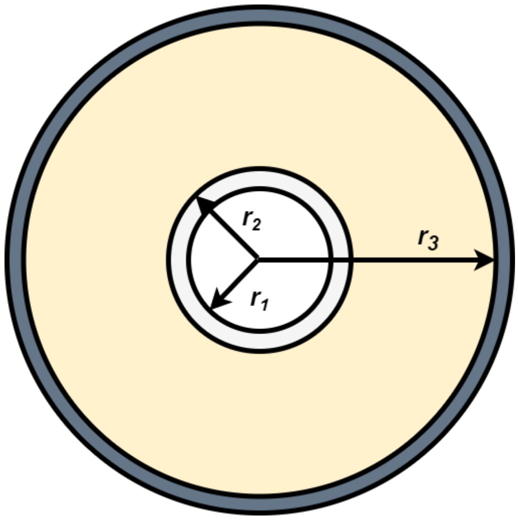

Figure 36: Generic pipe cross section with radii for inner and outer carrier pipe and outer PUR insulation.

Where $\dot{Q}$ is the heat transfer (here, heat loss), r_1, r_2 and r_3 are the radii as displayed in figure 36, t_i and t_o represent the temperature of the district heating water and soil respectively, L is the length of the pipe and λ_c and λ_i are the thermal conductivities of the carrier pipe and insulation. If both systems are to have the same heat losses while being subjected to the same conditions, $\dot{Q}$ is the same for both options and $t_i - t_o$ can be crossed out, giving:

$$\begin{aligned}(2\pi L_p\lambda_{c,p})^{-1}\ln(\frac{r_{2,p}}{r_{1,p}}) + (2\pi L_p\lambda_i)^{-1}\ln(\frac{r_{3,p}}{r_{2,p}})\\ = (2\pi L_s\lambda_{c,s})^{-1}\ln(\frac{r_{2,s}}{r_{1,s}}) + (2\pi L_s\lambda_i)^{-1}\ln(\frac{r_{3,s}}{r_{2,s}})\end{aligned} \tag{5}$$

where the subscripts p and s mean plastic/PE-RT and steel respectively. The contributions from the inner and outer convectional forces were ignored in equation 4 since they cancel each other out in the equation above. This is due to the fact that the surrounding soil can be considered stationary, implying the absence of convectional forces. Secondly, the two pipe types have approximately the same inner radius thus experiencing the same thermal convection. Rearranging the equation to solve for $r_{3,p}$ creates:

$$r_{3,p} = r_{2,p}\exp\left(2\pi\lambda_i L_p\left((2\pi L_s\lambda_{c,s})^{-1}\ln(\frac{r_{2,s}}{r_{1,s}})+(2\pi L_s\lambda_i)^{-1}\ln(\frac{r_{3,s}}{r_{2,s}})-(2\pi L_p\lambda_{c,p})^{-1}\ln(\frac{r_{2,p}}{r_{1,p}})\right)\right) \tag{6}$$

Although already provided earlier in the report, the relevant parameter values are reiterated in table 28. Minor variations exist between the two systems for each parameter but it is the 10.5 millimeter difference in the r_3 radius that is responsible for the major disparity in thermal insulation performance. Thermal conductivity values for the plastic and steel carrier pipes (λ_c) are taken from the website *Matmatch* [70].

Table 28: Dimensions and properties of the PE-RT and Steel pipes.

	r_1 [mm]	r_2 [mm]	r_3 [mm]	λ_c [W/m K]	λ_i [W/m K]	L [m]
PE-RT	39.9	55	88.3	0.4	0.022	116
Steel	41.3	44.5	87.1	46.8	0.023	123

Using the tabulated values as input, the result becomes $r_{3,p}$ = 99.1 mm which implies an increased PUR foam thickness of δ = 10.8 mm. If the equation would have been evaluated on a per meter basis, i.e. both systems having the same length, then the outcome would instead be $r_{3,p}$ = 102.8 mm and δ = 14.5 mm.

The suggested calculation contains a couple of flaws which can be amended by performing a more thorough analysis. One of the major errors is the negligence of other forces than thermal conduction in the pipes, i.e. thermal radiation. For this to be included, more information about the PUR foam material would be required. The thermal conduction could also be split into two parts, one for the conduction in the polymer matrix and one for the conduction in the cyclopentane gas. Once again, this would require more information about the material. Thermal convection in the foam can be assumed to be nonexistent as the size of the enclosed cells of cyclopentane are well below the threshold where the phenomena becomes significant. The proposed additional thickness can thus only serve as a lower boundary for a suggested increase. [26]

As a consequence of an improved thermal insulation through added material, additional PUR foam, diffusion barrier and HDPE mantel material would have to be manufactured. The additional amounts of material needed would be: 170 kg PUR foam, 46 kg HDPE and 1.5 kg aluminium barrier. Compared to the cut emissions associated with the reduced heat losses, the effect of an increased production is rather small. Figure 37 plots the effects on the considered impact categories from the increase in material production and reduced heat losses. The effects increased output from the transportation and installations phases are not considered as they are deemed either insignificant or impossible to concretize.

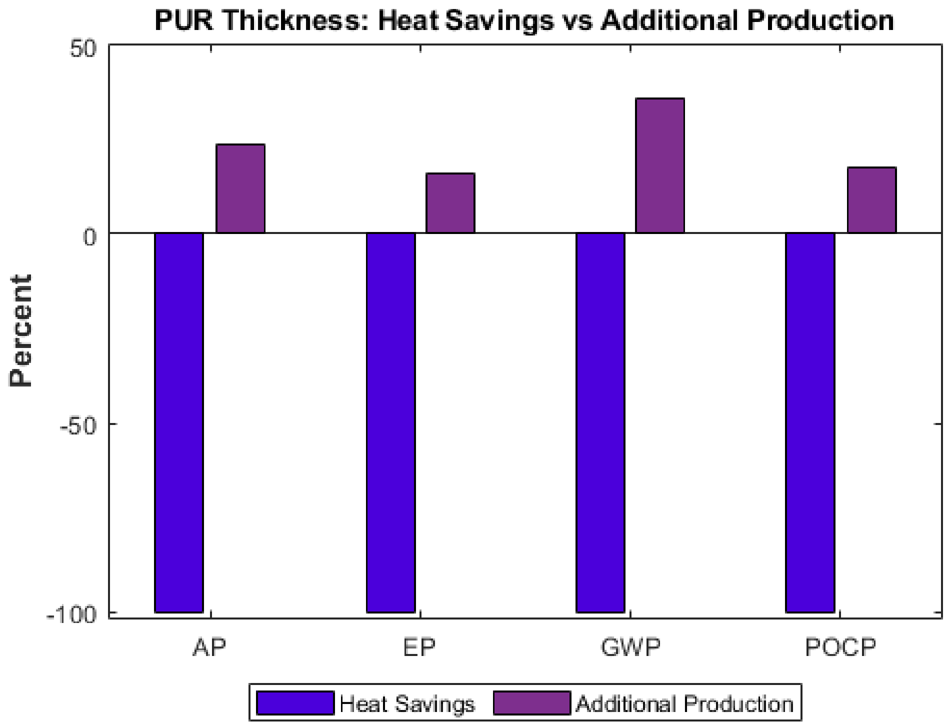

Figure 37: Parameter study: Effects from an increased production of materials compared with the negative (as in reductive) impact of reduced heat losses in the PE-RT system.

8.6 Altered Technical and Economic Life Time

Every life cycle phase starting from the extraction of resources to the installation can be seen as static contributors to the environmental impact categories. They happen once and generate a fixed amount emissions. The use phase is the only part not conforming to this rule and is instead a function of time. Looking at the results of the environmental impact assessment, it is evident that up until the beginning of the use phase the steel system has a larger impact on each category. With time as the use phase progresses, the balance gradually shifts. A breaking point is reached for each impact category at different times and as can be concluded from figure 24, all but the one in the case of GWP happen within the techno-economic life time of 30 years. If the emissions from the use phase are assumed to remain constant then they can be plotted as linear functions of time as in figure 38. This reveals the following breakpoints: GWP - 43 years, AP - 19 years, EP - 12 years, POCP - 12 years. Even though the techno-economic life time is set to 30 years, the pipes will most probably remain active long after that point in time.

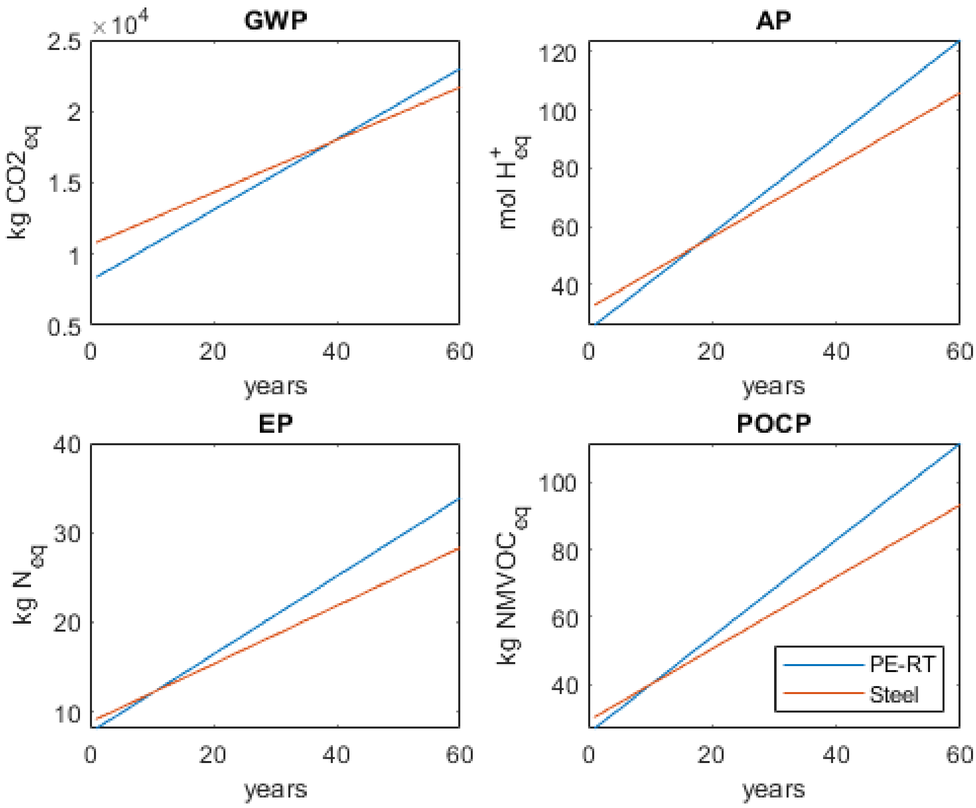

Figure 38: Parameter study: The evolution over time of GWP, AP, EP and POCP during the use phase.

9 Discussion

The point of the discussion is to summarise, scrutinize and assess the results of the study as well as the method and other relevant parts of the project. First the results of the project and major concepts are discussed followed by remarks on some of the life cycle phases. Lastly, the parameter analysis is expanded upon.

Looking at the comparison of the two product systems displayed in figure 24, it is somewhat surprising to see such a close resemblance between the two setups. PE-RT comes out as the worse alternative in every impact category but GWP where it is trailing steel with around four percent. A better understanding of the dynamic is achieved by shifting focus to the four subsequent graphs (figures 25 through 28) revealing for every impact category the effects from each life cycle phase. What is evident is the broad dominance of the use phase, only really being challenged by the manufacturing step in the GWP division. This explains the smaller gap between the two systems in GWP in the aggregated result relative to the corresponding relations in AP, EP and POCP. The GWP category is especially interesting due to the sort of reversely mirrored relationship between the manufacturing and use phases. Being inherently different, they still add up to approximately the same total. One could then argue that in this case that which is gained through lowered production emissions are lost because of higher heat losses.

It should really be emphasized that the major, and actually only, reason rendering PE-RT the less environmentally friendly option is its inferior heat insulation capacity. Every part of and input to the use phase is directly and linearly linked to the number of megawatt hours lost to the surroundings. In every other combination of impact category and life cycle phase, PE-RT is the preferable alternative. That being said, increasing the thickness of the insulation or maybe using another blowing agent to lower the heat losses to that of the steel system would not discard the impact of the use phase. It would still remain the largest single emitter but the overall result would shift in favour for the PE-RT option. It should not be forgotten that the network at Brunnshög actually is supplied with waste heat and that the decision to adopt a conventional heat production route was made with the intention to generalize the comparison. According to Kraftringen, only five percent of the yearly energy input to the LTDH network comes from the main city grid. Thus, specifically at Brunnshög, the PE-RT system is the better one in an LCA perspective.

What is not evident by simply looking at the projected results is the energy consumption of each activity and phase. The different parts of the life cycles are explained in detail and one should be able to appreciate the relative magnitude and energy requirements from one process to another. If that were not the case then some parts could seem inherently "dirtier" than others. A perfect example is the combustion of fuels for the purpose of heat generation. This particular activity is continuous and stretches over several decades. Compare this to the shipment of products from Logstor to Lund, an activity taking place only once. Without this added context it would be difficult to claim that either heat generation in an CHP plant or deliveries by truck are worse than the other. The point trying to be made is that by simply looking at the results in the environmental impact assessment, one should keep to the context and not interpret the conclusions as inherent qualities of one particular activity or phase.

LCA studies are naturally riddled with assumptions, all the way from the system boundaries to tiny details on a unit process level. It is difficult to contemplate the variability of the outcome if some detail had been altered, removed or included in the study. Given the balanced result, the question about uncertainty in modelling parameters is definitely relevant. An uncertainty analysis, using for example the Monte Carlo method, to assess the variability of parameters has not been included in the study. This is due to time-constraints and lack of experience. The approach has instead been to find and use the most general and representative pieces of data for each occasion. It is unclear whether the secondary data from the EF database have been subject to an uncertainty analysis. Yet, a couple of assumptions, decisions and processes could be put into question. The most obvious example is the exclusion of the final theoretical life cycle phase *Recycling*. At first glance from a materialistic viewpoint, the steel system would seemingly be the one to gain as steel is considered one of the most recyclable materials in the world. On the other hand PE-RT is also recyclable and as long as the recycled material is not used as direct input to the fabrication of new DH pipes, the amount of times a material can be recycled is irrelevant to the LCA. At this point one also has to acknowledge the state of the materials after 30+ years of service and how that impacts the recyclability. In the end, as mentioned in the system boundaries, all of this is negated by the simple fact that DH branches are left in the ground unless there is a clear incentive to remove them. As a consequence, finding a set of processes, not to mention LCI data, that represent the recycling of DH pipes could be really difficult. Any attempt to speculate on the subject could unfairly skew the final PE-RT and steel comparison. Everything considered, the decision to ignore recycling in this context is legitimate.

The production of biofuels provides a good look at the opposite side of the spectrum concerning the management of uncertainty in the model. Unlike recycling, this activity can not be excluded using similar arguments as before. This area is really challenging to analyze given the multitude of processes that happen over the vast time frame that is inherent to forestry and forest fuel production. It is also difficult to discern which exact activities that should be allocated to the fuel that end up at Örtoftaverket. Additionally, there is once again the complex aspect of indirect land use discussed in section 8.1. These intricacies are acknowledge by other parties as well. One example is an ongoing multi-million Swedish kronor project by the research program *BioInnovation* [71] that has the ambition of delivering concrete LCI data regarding forestry and related bioproducts. Since the data from that particular project is not yet publicly available at this point in time, several other approaches were attempted to assess the forest fuel supply-chain and its aggregated impact. Ultimately, these attempts all involved many assumptions and all produced widely different results which were far greater numerically than a set reference value provided by Kraftringen. Instead, a predefined process in the EF database representing sustainable forestry in Sweden and Finland was chosen due to its close proximity to the reference value.

The choice of functional unit at the early stages of the project should be scrutinized. The different trench lengths for the two product systems were based on the actual projected layout of the DH branch at Brunnshög. According to the conditions imposed by the case at hand, the FU can therefore be deemed justifiable. On the other hand, dividing the impact assessment results displayed in table 25 with the respective lengths of each system would reveal steel to be the better option on a per meter basis. Had for example a straight one hundred meter trench instead been selected as FU, steel DH pipes would be the clear winner. However, a functional unit is meant to be defined in a way that exposes both negative and positive characteristics of of a product. One of the clear benefits of the

PE-RT pipe is its flexibility and to purposely disregard this and features alike could prove more detrimental to the overall comparison.

The notion of uncertainty segues nicely into the complications of using free datasets and secondary data in general. As mentioned in section 4, the impact assessment method PEF was chosen since it did not require any fee to access its data. Most of the available predefined processes are provided by another major player on the LCA market, increasing the reliability of the information. On the other hand, it is unclear to what extent a similar but pay-to-use dataset differs in accuracy. The main problem however lies in understanding how well the provided secondary data reflect and correspond to the specific parts of the life cycle they are supposed to represent. This is especially confusing when having to combine it with information gathered on your own. For example, the provided data from the *World Steel Association* covering the entire cradle to gate of steel pipes contain 36 inputs and outputs in total to the process. They usually consist of a set of raw materials entering and residual products and emissions leaving. In contrast, data about the arguably insignificant production of brass couplings come from a predefined process in the EF database and includes well over a 1000 inputs and outputs in total. Most of these are fully negligible with flow quantities on the scale of 10^{-7} - 10^{-20} kilograms. Conveniently, the total impact of an EF database particular process usually boils down to the same data categories as emphasized by other sources, i.e. carbon dioxide, nitrogen oxides, sulfur dioxide etc. It is unclear if the tendency to include the same multitude of entries is shared by other database providers. This whole dilemma is also the reason why ozone depletion potential was omitted from the group of considered impact categories. ODP is a category that is more or less only affected by a small set of rare compounds that nowadays are seldom reported. The EF database's propensity to include such a wide variety of data categories no matter their size therefore sometimes give rise to local spikes in ODP from certain processes.

The PEF method also acts as an impact assessment method, imposing a select set of characterisation factors. This means that if the same study would have been done with the same collected LCI data but with a different impact assessment method, the result could have been different. This is due to, as discussed in the theory chapter, the fact that characterisation factors may vary from one method to another. For instance, methane has an alleged value of 36 kg $CO_{2,eq}$/kg according to PEF but for other methods like CML and ILCD the same figure is 25 kg $CO_{2,eq}$/kg (GWP100).

According to the results, the aggregated phase *Transportation* has a very small effect on the final outcome. This can be a bit misleading since this group only portrays the shipment of products to and from Logstor and not the transports occurring in the other parts of the life cycles. Moreover, the accumulated distances, in relation to the allocated cargo, covered by truck during the installation and use phase dwarf the ones to and from Logstor. Transportation as a distinct activity is therefore widely underrepresented in the LCIA result but the majority of its impact is simply presented under a different label. It could be argued that every transportation activity should be grouped together as one but this would in turn create a precedent where any set of resembling processes should see the same treatment. Ultimately, the most logical and convenient choice is to divide activities based on their location in the examined product's life cycle.

Another explanation for the low influence on AP, EP and POCP, are the low SO_2 and NO_x emissions from the combustion of diesel in heavy duty trucks which have seen a drastic reduction over the last two decades. From 1996 to 2009, the average sulfur content in diesel dropped from 400 ppm to 3 ppm. Similarly, nitrogen oxide emissions from heavy-duty vehicles have gone from 9.04 g/km (Euro I, 1996) to 0.507 g/km (Euro IV, 2009 and later). [43]

As a final remark on the subject of transportation, the emissions levels from trucks on a per kilometer basis are all evaluated based on a 61 percent payload. This is realistic in the case of deliveries to and from Logstor but probably inaccurate regarding the relocation of excavated masses during the installation and the shipment of fuels to Örtoftaverket. Consequently, these activities would probably in reality produce a larger or smaller amount of releases than what is included in the model. The reason this has not been addressed lies in the difficulty of finding a conclusive relationship between added payload and the subsequent increased fuel consumption and released emissions.

The resource extraction and refinement phase is the one with the heaviest presence of secondary data. This is quite normal in LCA studies since this part usually involves numerous product flows and activities. For projects like this one which have a direct access to information regarding the second half of the considered life cycle but not the first, the use of some sort of database is often required to fulfill the scope of the project. Thankfully, most of the raw materials that are used in the fabrication are very common and usually have one or more related industry associations connected to them. This makes for reliable data whether they are available through LCI databases or in separate reports. As expected, the production of the steel pipes is accompanied by a sizeable set of emissions. The steel alone actually adds more to AP and GWP than the extraction, refinement and preproduction of the entire PE-RT system.

As was touched on in the inventory, the installation phase is probably the one with the largest amount of individual assumptions connected to it. However, they are all rather small and an increase or decrease within a realistic range of variance of an affected variable would not produce a significant change to the overall result. The activity asphalting which is not covered in the report at all could potentially have had a relatively large impact. It was the only area left out of the model solely due to time constraints but it was also the first one in line to be omitted. The asphalt in itself is not necessary for the fulfillment of the functional unit and seeing as both systems would use more or less the same amount of material and labour, their effects in a comparative LCA cancel each other out.

The primary DH network in Lund and neighboring areas are supplied by other furnaces and equipment than that which is found at Örtoftaverket. The reason why it was chosen to represent the entire arsenal of production units was the availability of data and once again the lack of time. Unfortunately this implies disregarding parts of the total produced heat originating from heat pumps which are electrically powered. On the other hand, the equipment is at some rate continuously updated and processes are made more efficient or climate friendly with the passing of time. For example, peat and the previously used fossil oil have been removed and replaced as input to Örtoftaverket. Going in to the 2020s and a new DH generation, it felt adequate to let the technology reflect the highest current standards. This reasoning is also applied to the transportation activities where Euro VI emission levels were applied to every truck in the model even though this might not necessarily be a correct assumption.

The parameter analysis investigated features of the system that, if altered or inspected differently, would impact the overall outcome in a significant way. The data pertaining to the alternative production routes of both steel and polyethylene are too imprecise to directly include in and compare to the created system model. Nonetheless, the two results displayed serve as an indication of the relative difference between the applied production routes and that which could have been if the Chinese steel and Brazilian sugar cane routes had instead been considered.

The decision to stick to the non-biogenic emissions associated with the combustion during heat generation in main ALCA was made partially to adhere to the established industry rules but also as a way to not drop the focus from the other life cycle phases. This being an immensely complex and broad subject, it is fair to assume that more aspects and details than what can be presented in a two-page analysis are required to make an well-informed evaluation of the status of biogenic CO_2 emissions. Yet, with the unrivaled possible implications posed by biogenic carbon dioxide, it simply can not be overlooked and should remain as a point of discussion in any and every forum. Interestingly, if the main comparison had included biogenic emission from combustion but also acknowledged the fact that only 5 percent of the supplied heat comes from the main city grid, the GWP output of the use phase and the corresponding bars in figure 27 would still be more than twice as big as their current size.

As suggested in section 8.5, an added 1.1 centimeters (radially) of PUR foam in the PE-RT pipes could put it on par with the steel system in regards to thermal insulation performance. This would however create problems outside the scope of an LCA such as an undesirable level of rigidity, making the PE-RT product less attractive in general. Another proposed solution is to utilize another blowing agent with better properties. This was actually the initial idea according to Logstor and Kraftringen and it was close to having been realized. Unfortunately the plan was scrapped due to legal issues.

10 Conclusions

This report compares the environmental profile of two types of district heating pipes by conducting a life cycle assessment of both systems. The study is case-specific but tries nonetheless to reach general conclusions about the considered products.

The result of the main comparison, and concurrently the answer to the first research question, is that the PE-RT system performs slightly worse in the impact categories *Acidification Potential*, *Eutrophication Potential* and *Photochemical Ozone Creation Potential*. It is only in regards to *Global Warming Potential* that the steel system has a more significant impact. Overlooking any implication or opinion about the products and their associated performance, the similarity between the two studied systems is satisfying since it indicates that both options have been treated equally. Their life cycles are very similar and should therefore logically give rise to similar amounts of emissions. On the other hand, and as discussed regarding the reliability of different LCI sources, another study investigating the same thing but using a slightly different method could arrive at another set of conclusions.

Concerning certain areas with a large amount of associated emission or so called hotspots, the use phase followed by the manufacturing phase are the two most noticeable life cycle phases. More specifically, the most significant activities emission-wise consist of the combustion of fossil fuels to generate heat for the DH network, steel pipe manufacturing, production and transportation of biofuels as well as PE-RT granulate production. As explained earlier in the report, it should be emphasized that the network at Brunnshög is in actuality supplied by waste heat rather than heat from a CHP plant. This practically eliminates the impact from the use-phase, rendering the PE-RT system the more environmentally friendly option for this specific scenario.

The parameter analysis reveals that reasonable changes to key areas of the two product systems mostly scale their respective impacts linearly and moderately. The large exception is the choice of disregarding biogenic carbon dioxide emissions during heat generation which if included completely changes the end result on a total and phase specific level.

Using this report as a basis for future investments could be an unwise decision. Given the close resemblance between the two systems in an environmental perspective, moderately sized errors or alternative approaches could change the outcome of the study. Other non-environmental aspects not covered in this study (improved installation procedure, costs etc.) could as of now prove to be a better metric when deciding between one pipe system or another. Furthermore, as mentioned throughout the report, the district heating domain finds itself currently in a transitional period where newly introduced concepts and technologies still need some time to mature. The results should not discourage further research and investments in new DH technologies as improvements can and have to be made in order to reach the environmental goals set by society.

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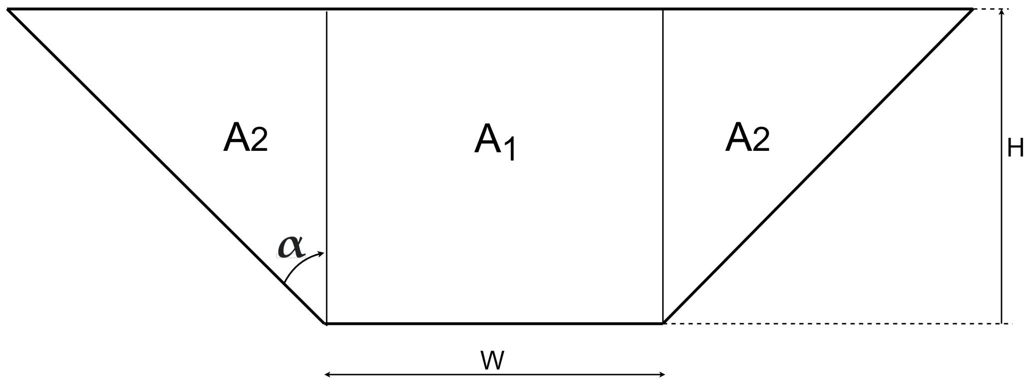
Appendix: Calculations and Formulas

Trench Dimensions

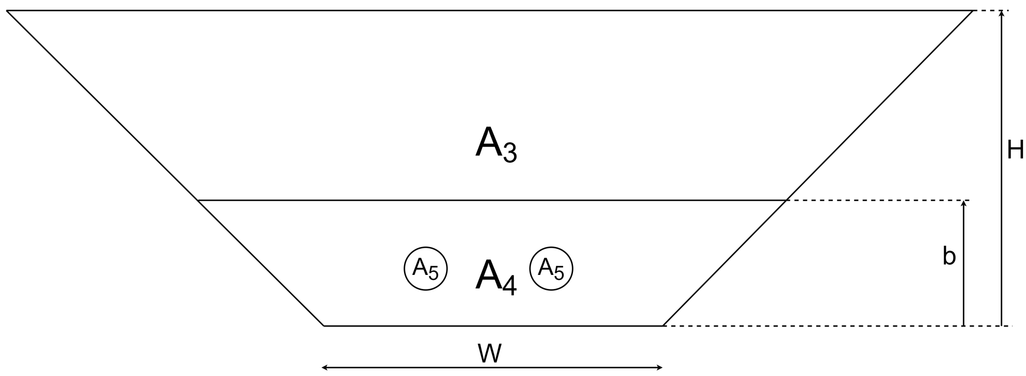
Calculations regarding amounts of excavated and refilled masses.

$$A_{tot} = A_1 + 2 * A_2 = W * H + H^2 * \tan(\alpha)$$



$$A_4 = W * b + b^2 * \tan(\alpha) - 2 * A_5 = W * b + b^2 * \tan(\alpha) - 2 * \frac{\pi}{4} D_y^2$$

$$A_3 = A_{tot} - (A_4 + 2 * A_5)$$



Excavated Masses: $m_{em} = A_{tot} * L * \rho_{em}$

Purchased Aggregates: $m_a = A_4 * L * \rho_a * 1.15$

Refilled Excavated Masses: $m_{rm} = A_3 * L * \rho_{em}$

Where ρ_{em} = 1600 [kg/m^3] and ρ_a = 1600 [kg/m^3] are the densities of the excavated masses and purchased aggregates respectively, L is the length of the trench for each system. The factor 1.15 is an estimation made by people in the industry representing the additional amount of gravel needed due to the compression of the material.

Alternative Production Method

CHP plants produce both electricity and heat. The conversion efficiency from the input fuel to either electricity or heat are not the same. Consequently, the two energy carriers have to be assigned a separate percentage of the associated emission outputs. The typical allocation method used in the Swedish energy industry for this purpose is called the alternative production method (or "Alternativproduktionsmetoden" in Swedish).

$$F_{i,h} = \frac{\frac{E_h}{\eta_{i,h}}}{\frac{E_h}{\eta_{i,h}} + \frac{E_e}{\eta_{i,e}}}$$

The subscript i represents one type of fuel and h and e stand for heat and electricity respectively. $F_{i,h}$ is the final allocation factor for heat and E is the total energy produced of heat and electricity respectively. η is the ratio of energy produced per unit energy contained in the fuel.

Table 29: Specific fuel allocation factors used in the alternative production method

	$\eta_{i,h}$	$\eta_{i,e}$
Forest Fuel	0.86	0.33
RWW	0.86	0.33
Heating Oil	0.89	0.44

This method can be used conversely to attain the corresponding factor for electricity by simply replacing the numerator with $E_e/\eta_{i,e}$. Using the given information in the report, the factor $F_{i,h}$ actually comes out to 0.466 but Kraftringen's own calculations yield a value of 0.51 which is the one used in this report. The information in this segment comes from the industry association Energiföretagen but is currently unavailable at their website.

Forest Fuel Production

This section aims to present the deduction process for estimating the impact from the production of biofuels. it includes the activities, *chipping, harvesting* and *forest management*. For the sake of lucidity, it is presented in a chronologically reversed fashion.

The energy input to the generation of heat at Örtoftaverket can be divided based on types of fuels used. For each MWh of heat produced 54.83 percent comes from RWW, 44.86 percent from forest fuels and 0.3 percent from oil. Since the production of RWW is allocated to other products' life cycles, only the production of forest fuels is included. The considered forest fuel has an alleged energy density of 2.8 MWh/tonne. The required amount of forest fuel to supply 1 MWh of heat (=0.449 MWh forest fuel) then becomes:

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	MWh_{ff}/MWh_h	$tonne_{ff}/MWh_h$	$tonne_{ff}$/year	$tonne_{ff}$/(30 year)
PE-RT	0.449	0.16	3.56	107
Steel	0.449	0.16	2.65	80