Life Cycle Assessment of District Heating Pipes; Comparing Polyurethane with Polyethylene Terephthalate Insulation

Oluwaseun Abegunrin
6050674

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Supervisor I
Prof. Dr.-Ing. Ingo Weidlich

Supervisor II
M.Sc. Lucia Doyle Gutierrez

Resource Efficiency in Architecture and Planning

HafenCity Universität Hamburg

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Author: Oluwaseun Abegunrin
Supervisor I : Prof. Dr.-Ing. Ingo Weidlich
Supervisor II: M.Sc. Lucia Doyle Gutierrez

Resource Efficiency in Architecture and Planning (REAP)
HafenCity University Hamburg

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ABSTRACT

District Heating (DH) system has proven to be a viable solution for delivering heating, hot water, and cooling services to the end-users, in that it represents the most suitable energy solution for satisfying urban heat and cold demands. So, in order to keep evolving, district heating must constantly develop in response to the growing demands of a society striving towards sustainability. By this, the sustainability of this system needs to consider further aspects of material use and deploy a large-scale material efficiency which could be a crucial factor in obtaining a variety of additional environmental and economic benefits. In a typical DH distribution system, the pipe is an integral part. The commonly used DH pipe is the pre-insulated bonded pipe with steel carrier pipe, rigid polyurethane (PUR) foam, and high-density polyethylene (HDPE) casing. However, PET foam has been suggested as a suitable substitute for PUR foam.

This thesis therefore presents a comparative study to benchmark the environmental impacts for the manufacturing of polyurethane (PUR) foam insulated pipe and a conceptual polyethylene terephthalate (PET) foam insulated pipe based on Life Cycle Assessment methodology. The functional unit is taken to be "the production of 2.42 m length of a DN100 pre-insulated pipe".

The results of life cycle assessments show that the process of manufacturing PUR foam insulated pipe has the largest environmental impacts across the selected impact categories, while the emissions are mostly noticeable in climate change and fossil depletion, which is mostly influenced by raw materials extraction and refinement. An evaluation of material layers indicated that steel pipe gives off the highest emission of all the material components in the pipe and methylene diphenyl diisocyanate (MDI) in the PUR foam. A comparison of insulations materials also showed that virgin PET foam has 28% less impact and when virgin PET in the PET foam is replaced with recycled PET, the impact was further reduced by up to 60%, thereby confirming it to be a suitable alternative. Furthermore, a sensitivity analysis showed that Substituting virgin PET foam with recycled PET foam in the overall system achieved the highest environmental benefits by approximately 12% and this savings in impacts is noticeable across almost all impact categories.

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ABBREVIATIONS

CFC	Chlorofluorocarbon
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
DH	District Heating
EP	Eutrophication Potential
GHG	Green House Gases
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
MDI	Methylenediphenyl diisocyanate
NMVOC	Non-methane Volatile Organic Compound
NOx	Nitrous Oxide
NO_2	Nitrous dioxide
PET	Polyethylene terephthalate
PUR	Polyurethane
rPET	Recycled Polyethylene terephthalate
SO_2	Sulphur dioxide
VOCs	Volatile Organic Compounds
vPET	Virgin Polyethylene terephthalate

1.0 INTRODUCTION

Over the years, district heating (DH) has proven to be a viable solution for delivering heating, hot water, and cooling services to the end-users. It represents the most suitable energy solutions for satisfying urban heat and cold demands (Buffa, 2019). The main idea centres on the use of local heat and fuel sources that normally would be lost or remain unused to generate heat (Lund et al., 2014). It involves the distribution of heat (hot water or steam) from a central location, through a network of pipes to individual houses or blocks of buildings for purposes such as space and water heating (Rezaie & Rosen, 2012).

According to Werner (2013), district heating significantly increases the overall energy system efficiency since the heat supply is coherent with the generation of electricity, refuse incineration, or industrial processes. It also employs the use of geothermal heat sources or biomass fuels thereby reducing the demand for commercial fossil fuels for heating which in turn reduces carbon dioxide emissions (dhcplus, 2012).

District heating has several advantages. From an economic standpoint, a high conversion efficiency and less maintenance requirement reduces the cost of heat production. Customers benefit from decreased heating equipment investment costs as well as simple, continuous, reliable, and direct heat supply. Furthermore, because home boilers are no longer required, more space in structures is available (Frederiksen & Werner, 2013). Also, For DH, a variety of energy sources can be used. By replacing natural gas combustion in household boilers, this increases the energy system's flexibility and reduces reliance on primary energy and fossil fuels (Persson & Werner, 2011). The increased supply has additional environmental benefits, as centralized operations are more efficient and make carbon capture easier to achieve. Additionally, since household boilers have been removed from homes, pollutants are no longer emitted directly in the homes.

In Europe, the utilization of District Heating is not evenly distributed. In some countries, it is almost non-existent while reaching as high as 70% in others. In general, it currently serves approximately 60 million EU citizens, with an additional 140 million living in cities with at least one DH system (Euroheat & Power, 2018a). There are more than five thousand district heating systems in Europe, currently supplying more than 10% of total European heat demands with an annual turnover of €25-30 billion and 556 TWh heat sales. It is mainly the northern, central, and eastern European countries that have a high penetration of District Heating, while Poland and Germany have the largest total amount of district heat delivery (Frederiksen & Werner, 2013).

It is common for the evaluation of the efficiency of district heating by the temperature at which heat is given, the heat source- whether it is a central or individual heating system, and the choice of pipes used for distribution (Persson, 2011). Although District heating is considered to be environmentally friendly for heating buildings and is recognized as one of the solutions to mitigate climate change, it is not without its issues. The choice of district heating pipe size influences the environmental impacts from extraction, through the type of material used, and the environmental impacts from pipe production, through the energy requirement (Balode, Dolge & Blumberga, 2021). The characterization of emissions has benefits at the global level, by assessing the overall contribution to the greenhouse effect, and on the local level, by identifying potentially harmful pollutants and studying their dispersion in the territory (Ravina, Panepinto & Zanetti, 2018).

However, to integrate into a sustainable society, district heating must constantly develop in response to the growing demands of a society moving toward sustainability.

1.1 Problem Statement

Polyurethane is a widely used material; however, it does not exist without isocyanates and polyols. It is formed by simultaneous polymerization and expansion in a formulation containing an isocyanate, a polyol, and a blowing agent at a low boiling point (ISOPA, 2020). The handling of Isocyanates is problematic in every working environment as they are highly toxic and can cause allergic reactions in humans (Mangs 2005). In the case of a PUR foam, isocyanates molecules in it can be released if the chemical links are broken in the event of heating, such as when district heating pipes are welded together during the construction of the district heating network (Bergström 2002).

In view of this, the EU in August 2020 restricted the use of Isocyanates in the manufacturing processes following the Risk Management Option Analysis (RMOA) and subsequent filing by the German Institute of Occupational Safety and Health (BAuA) in 2014. The restriction may limit or ban the manufacture, placing on the market, or use of this substance to protect human health and the environment in the near future (ISOPA, 2020). Consequently, the need for a suitable alternative for PUR foam in DH pipes manufacture has become more necessary than ever.

Furthermore, what happens to PUR at its end-of-life has been a subject of increasing concern. PUR materials are made from non-renewable petrochemicals, have a short lifespan, and pose a risk to the environment (Berente, 2006). The presence of CFC (chlorofluorocarbon) type gases in the material makes its recycling process more complicated. Its combustion also poses the risk of the formation of nitrogen oxides (NOx, N_2O), ammonia, pyridines, and other hazardous or toxic nitrogen compounds because of the high nitrogen content of the material (Zevenhoven, 2004). As a result of this, as well as a growing focus on concerns such as waste disposal and non-renewable resource depletion, the research and production of alternative materials that are from natural sources and/or recyclable are generating a lot of interest.

Similarly, a research project is being carried out in the HafenCity University Hamburg, which entails the replacement of PUR foam with a more sustainable material like PET since PET could serve this purpose in standard steel medium pipes with HDPE casing (Doyle, 2021). Therefore, this thesis intends to evaluate the environmental issues posed by different components in PUR-insulated pipe as against the conceptual PET-insulated pipe by carrying out a life cycle assessment (LCA).

1.2 Aim and Objectives

The goal of this thesis is to benchmark a new PET insulated district heating pipe against the state of the art: bonded PU pre-insulated pipe. It aims is to investigate whether PET foam insulated pipes have the potential to favourably compete and possibly replace traditional PUR foam insulated pipes from a circular economy perspective.

This study will help to compare the environmental performance and impacts of the products to be analysed. The results from the LCA will be used to decide which of the pipe types has the best environmental performance and to identify success factors and negative contributors in the product's life cycle. This will be achieved by identifying environmental hotspots. It is possible for the outcome of this study to serve as part of a guide for decision-making authorities to determine the future of material flows within the district heating infrastructure setup and practices. In addition, researchers can hinge on the outcome of the study to further develop areas where further research may be required in a wider context. Since the study is not case-specific, the results can both be applied to varying sustainability work across different pipe scenarios within the district heating distribution framework as well as a communication tool.

To achieve the intended purpose of this study, the Life Cycle Assessment will involve the following:

1. Compilation of the Life Cycle Inventory (LCI) for both pipe models
   - Standard: steel medium pipe, PU insulation, PE casing, eventually aluminium diffusion barrier.
   - New design: steel medium pipe, PET insulation, PE casing, eventually aluminium diffusion barrier.
2. The realisation of a comparative Life Cycle Assessment from the extraction phase to the factory gate (Cradle to Gate)

1.3 Outline of the Thesis

This section presents how this thesis has been structured. The following chapters in this thesis include the theoretical framework, research design and methodology, an LCA according to the ISO 14040/44 standard and its results, and the results from the study.

Chapter 1: Introduction
Chapter 2: Background to the Study
Chapter 3: Research Methodology – This section includes a description of the research design of the thesis and the theoretical framework of the methodology used.
Chapter 4: Comparative LCA of District Heating pipes – Goal and scope definition, Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation.
Chapter 5: Discussion and Conclusion – consists of a discussion of outcomes, limitations to the study, reflections and conclusions based on the LCA study, and further suggestions.
Chapter 6: References

2.0 BACKGROUND

Heating is unarguably the largest single energy end-user. It is responsible for approximately 50% of total final energy consumption globally (IEA, 2019). In Europe for example, 68% of its total energy demand serves the primary purpose of meeting space-heating requirements, while 14% goes for producing warm water (ECTP, 2010). The ever-increasing demand for heating in different sectors, along with more preventative regulations on greenhouse emissions, has forced different countries to seek new alternatives to heat buildings such as district heating systems (DHS) (Talebi, et al., 2016).

Lund et al. (2014) provided an overview of the development of district heating systems over several years. The earliest generations of district heating systems used pressurized steam. It utilizes a central supply of heat at immediately useful temperature levels that were distributed to buildings. The system evolved as the heat carrier was changed from steam to superheated water and signifies the onset of the 2nd generation district heating. Also, according to Vega (2020), the 3rd generation was introduced in the 1970s where insulated pipes installed underground were used to promote energy efficiency and to eliminate oil dependence by using other energy sources. This design is still very much commonly used around the world today. This will be the main focus of this thesis. The technology has continued to evolve and is now at the phase where heat loss and the possibility of district heating systems to operate at lower temperatures using lighter and cheaper materials in piping is the focus (4th & 5th generation) (Nussbaumer & Thalmann, 2014).

Table 1: Evolution of district heating systems (Adapted from Lund et al., 2014)

Generation	Period	Heating Medium	Temperature (°C)
1st Generation (1G)	Mid 1800s–1930s	Steam	<200
2nd Generation (2G)	1930s–1970s	High temp. pressurised water	>100
3rd Generations (3G)	1970s–2010s	High temp. pressurised water	=<100
4th Generation (4G)	2010s–present	Low-temp. water	30–70

2.1 District Heating Network

The work of district heating networks is undeniably influenced by the management of the distribution networks (Lund, 2014). There are typically two major components of a district heating network:

a. A single heat centre with one or more heat sources to manage demand and offer backup/optimum supply.
b. A spatial heat transmission and distribution network is made up of the following:
    i. A major network that delivers and distributes hot water from the heat source to the substations (mostly customers substations).
    ii. Substations that serve as a link between the primary and secondary networks.
    iii. Secondary network to transport water to the final consumer (mainly located in buildings or houses) (Delangle, 2016).

The diagram in **Figure 1** depicts the operation flow of a typical district heating system. After generation, heated water is pumped under pressure through a closed system of supply and return pipes that are interconnected underground. As a result, the water in the pipes serves only as a heat energy carrier. By using temperature differences with other counterflowing water streams, this heat energy can be supplied or removed from the heat grid using heat exchangers (British Plastic Federation, 2017). The primary transportation network connects the heat producer to the heat exchange substation, from whence the heat energy is distributed to the consumers through the secondary distribution network. In comparison to the primary distribution network, the secondary distribution network often has smaller pipe sizes and lower operating temperatures. Normally, heat loss in a DH network is between 5% and 10% but can go as high as 20% to 30% (IEA ETSAP, 2013). Therefore, the effectiveness of an optimal heat distribution system largely depends on pipe size, feed, outdoor temperatures, user density, and most importantly, the thermal insulation of pipes (Mangs, 2005).

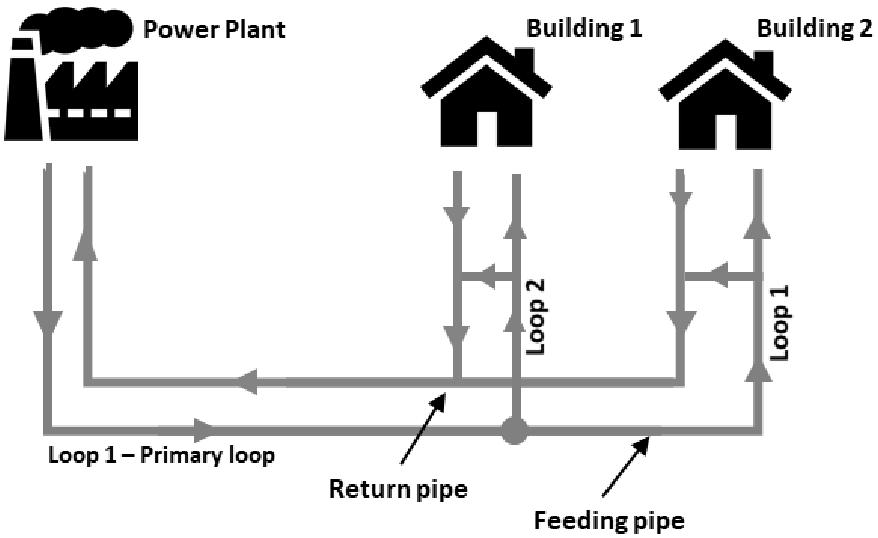

Figure 1. Schematic representation of district heating (*Adapted from Gambarotta, et al., 2017*).

The principal component of a district heating network is the primary network that transports and distributes the hot water that must be carefully constructed to minimize heat losses while maintaining a low operating cost (Frederiksen & Werner, 2013). The core network is made up of the following:

i. Pipes – In district heating networks, the importance of pre-insulated pipes cannot be over-emphasized as it forms an integral part of the system (Persson, 2015). In most cases, two pipes, a supply pipe, and a return pipe are buried underground. For low-energy applications, some old networks simply used a supply pipe, while others can use three pipes (plus a recirculation pipe) (Dalla Rosa, A., et al., 2011). There are many different types of district heating pipe, but the commonly used one is the pre-insulated bonded pipe. The pipe consists of an internal steel carrier pipe, an intermediate insulating layer of rigid polyurethane (PUR) foam, and an external casing made of high-density polyethylene (HDPE (Fröling et al., 2004). Due to the high pressure

and heat-resistance required, cross-linked polyethylene (PE-Xa), polybutylene or steel can also be used in the production of the outer casing of the pipes. (Battenfeld-Cincinnati, 2019).
To avoid fatigue and rupture, pipe designs are primarily stress-based. Pipe insulation can help to reduce heat losses in the network. According to Olsson, (2001), polyurethane foam is commonly used as it has a very low thermal conductivity, which is due to the porous structure and the low conducting gases trapped in the cells of the foam. Over a considerable part of a DH pipe's lifetime, the gas content of the foam changes thereby significantly influencing its thermal performance. The losses can also be reduced by locating both pipes within a shared circular insulator with an exterior casing (twin pipes). It allows for easier heat transfer from the supply pipe to the return pipe, allowing heat losses from the supply pipe to be reused to warm the return water (Delangle, 2016).

ii. Distribution pumps – Varied flow rates are regulated by the use of pumps. Because the network cannot function without them, many distribution pumps can be placed in parallel and run at the same time. Also, to adjust the pressure, pressurization pumps are used to keep a constant amount of water in the system. They're also used to keep water from overheating. They're frequently connected to expansion tanks, which allow surplus water to be removed from the system.
iii. A leakage and breakage monitoring control: Leakage wires are commonly connected to a control box into the pre-insulation of pipes. When the circuit resistance is changed, they allow for the detection of any leakage.

The utilization of district heating systems is not without its issues. Mangs (2007) pointed out that during the use of district heating pipes, emissions from the heat produced to compensate for the heat losses give rise to environmental impacts. In a study, Fröling et al., (2002) compared the environmental consequences of heat losses during the use phase of district heating pipes to the impacts from pipe production and network construction and discovered that the use phase of district heating pipes is the most important of the life cycle phases studied. As a result, it's critical to keep heat losses from pipes to a minimum.

The thermal insulation from polyurethane foam gives more advantages in that it has higher mechanical strength, lower thermal conductivity, and very good adhesion between the service steel pipe and the HDPE casing pipe (Jarfelt & Ramnas, 2006). One important attribute of the foam is the blowing agent used. The blowing agent influences both the initial insulating capacity of the foam and the ageing characteristics, due to differences.

Jarfelt and Ramnäs (2008), then suggested that polyethylene terephthalate (PET) foam has the potential to compete successfully with PUR foam as it is impermeable to liquid water and only vapour can diffuse through it. When compared to PUR foam, its vapour resistance is approximately 10 times greater than for a regular PUR foam. In addition, the researchers opined that since the effective diffusion coefficients of oxygen, nitrogen, and carbon dioxide in a PET foam are about 5-15 times lower than those in a PUR foam, therefore, there is a clear indication that the long-term thermal performance of PET foam is better.

From an environmental perspective, Mangs et al., (2006), just like other researchers opined that carbon dioxide blown PET foam insulated DH pipes have the potential to compete well in terms of environmental performance as against cyclopentane blown PUR foam insulated pipes, as long as practical technologies to ensure low-density PET foam are discovered. This will be the main area of concentration of this thesis.

2.2 Literature Review

When it comes to the life cycle assessment of district heating systems, the amount of studies conducted on the topic is not as elaborate as on other subjects. But some articles written specifically on the subject which were consulted during this thesis are as follow:

a. Fröling M., Holmgren C., & Svanström M. (2004). Life Cycle Assessment of the District Heat distribution System, Part 1- Pipe Production. This paper presents a life cycle assessment of the production of district heating pipes, based on a cradle-to-gate life cycle inventory commissioned by the Swedish District Heating Association.
b. Fröling M., Holmgren C., & Svanström M. (2004). Life Cycle Assessment of the District Heat distribution System, Part 2 - Network Construction. This paper presents a life cycle assessment of the construction of district heating pipe networks, based on a gate-to-gate life cycle inventory
c. Fröling M., Holmgren C., & Svanström M. (2004). Life Cycle Assessment of the District Heat distribution System, Part 3 - Use Phase and Overall Discussion. The paper presents an evaluation of the use phase of district heat distribution, focusing on the long-term thermal performance of different district heating pipes.
d. Mangs, S., (2005). Insulation materials in district heating pipe Environmental and thermal performance of polyethylene terephthalate and polyurethane foam. Thesis for the degree of Doctor of Philosophy – In this literature, the long-term environmental and thermal performance of different insulating materials were studied and the performance of polyethylene terephthalate (PET) foam as a possible replacement alternative to PUR foam was also investigated from a life cycle assessment.
e. Armacell, (2018). Life cycle assessment of PET Foams. Armacell

3.0 RESEARCH METHODOLOGY

To achieve the aim and objectives of this thesis, a comparative Life Cycle Assessment (LCA) of a bonded district heating pipes with PUR and PET insulations respectively is carried out in accordance with ISO 14040/44 (2006). The outcome from the study is used to determine which pipe type has the best environmental performance by identifying important environmental impacts and hotspots during pipe manufacture. As a starting point, it is deemed necessary to briefly discuss a general overview of the LCA methodology in this section. Only a description of the main features and the basic concept is presented. The actual LCA conducted for this study is presented in the next section.

3.1 Life Cycle Assessment (LCA) Concept

Environmental LCAs have been used for a relatively long time but during the last decades developed further in terms of methodology, databases, consistency, and thereby the quality and reliability of the results (Finnveden et al., 2009). The concept is standardized internationally by the International Organization for Standardization (ISO) in ISO 14040: 2006 and ISO 14044: 2006. When it comes to district-heat production, the goal of LCA is to provide a holistic perspective of the emissions and resource requirements of a product system, which implies that all activities involved in the extraction, refining, transportation, and use of the fuels are taken into account.

The life cycle of a product begins with the extraction of raw materials from the earth, continues with manufacturing, transportation, and use, and concludes with waste management, which includes recycling and final disposal. There are emissions and resource consumption at every phase of the life cycle as such the environmental impact of a product's or service's complete life cycle must be considered. (Babu, 2006).

The methodology is recognized as one of the most powerful and widely used tools for undertaking holistic environmental sustainability assessments, as it assesses the product's environmental impacts with a multicriteria approach (Hicks, 2010). The principle entails calculating the materials and energy flow inputs, as well as the emissions, at all phases of a product's life cycle. Beyond climate change, which is the most common single parameter evaluated when analysing environmental performance, LCA provides a broader view because it can be used to evaluate a broader range of environmental impact categories. (LowTem, n.d.).

The development of the LCA in this thesis follows the ISO 14044 standard, which identifies four phases as shown in **Figure 1** below:

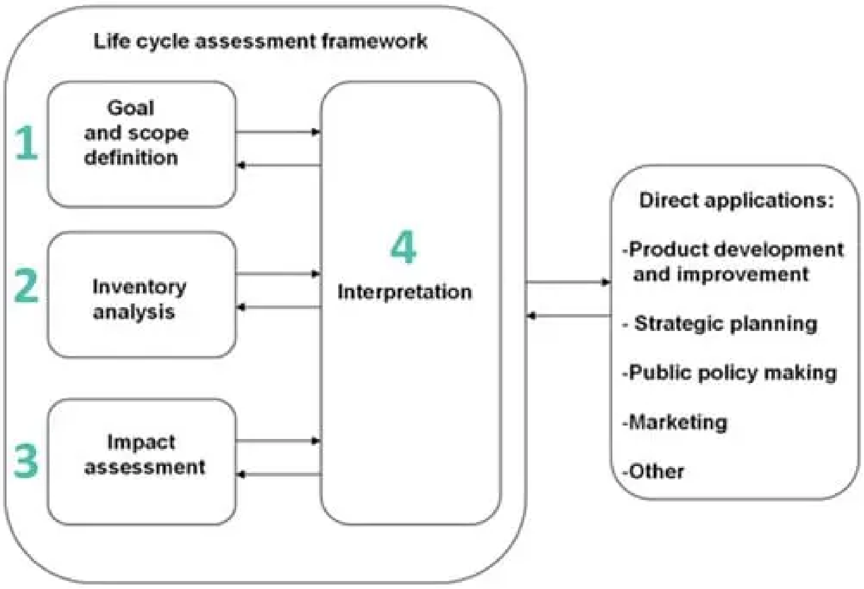

Figure 2: Life Cycle Assessment Framework

3.1.1 Goal and Scope Definition

An LCA starts with a well-considered and deliberate definition of the goal of the study. The goal definition sets the context of the study and is the basis of the scope definition. This phase aims to define how big a part of the product life cycle will be taken in assessment and to what end the assessment will be serving (Curran, 2017). The LCA lays out the parameters of the study and indicates to whom the assessment will be delivered. The goal and scope define exactly what is being studied, which functional areas are being analysed, and which precise inputs and outputs are related to the product or service. Additionally, it expresses the limitations and assumptions of the study.

The definition of the goal and scope is the critical part of an LCA due to the strong influence on the result of the LCA. This phase contains the goal definition, scope definition, functional unit, system boundaries, data quality, and critical review process (EEA, 2001).

3.1.1.1 Goal Definition

The goal definition determines the level of sophistication of the study and the requirements for reporting (Bjørn, et. al., 2018). It is important to determine the intended application of the LCA results at the onset because it influences the later phases of an LCA. According to the ISO standard (ISO, 2006), "the goal of an LCA study shall unambiguously state the intended application, including the reasons for carrying out the study and the intended audience, i.e., to whom the results of the study are intended to be communicated." It generally contains six aspects:

- Intended applications of the results
- Limitations due to methodological choices
- Decision context and reasons for carrying out the study
- Target audience
- Comparative studies to be disclosed to the public

- Commissioner of the study and other influential actors (Bjørn, et. al., 2018).

3.1.1.2 Scope Definition

The scope definition is the second phase of an LCA. It determines what product systems are to be assessed and how this assessment should take place. This describes the detail and depth of the study and shows that the goal can be met with the actual extent of the limitations. In determining the scope of a study, it is important to consider the product system, functions of the product system, the functional unit and reference flow, system boundary, Allocation procedures, and data quality requirements (Guine´e, 2015).

3.1.1.3 Functional Unit

The functional unit is the quantified definition of the function of a product. It should represent the performance of the functional outputs of the product system. It provides a reference to which inputs and outputs are related. Part of defining a functional unit is the definition of a reference flow. The reference flow is the measure of product components and materials needed to fulfil the function, as defined by the functional unit. All data collected during the inventory phase is related to the reference flow. In other words, all data used in the LCA must be calculated or scaled in accordance with this reference flow (GaBi, n. d.).

The functional unit is a key element of LCA that must be clearly defined. The functional unit is a measure of the function of the studied system, and it provides a reference to which the inputs and outputs can be related. To compare two products, their functional units must be equivalent.

3.1.1.4 System Boundary

The system boundaries determine which unit processes to be included in the LCA study and which inputs and outputs should be included. Defining system boundaries is partly based on a subjective choice, made during the scope definition phase. The selection of which processes to include in the system depends on the goal for the study and the intended application of the results (Pålsson & Riise, 2011). In practice, the work with defining system boundaries is aided by developing an initial flowchart of the product system, which shows the processes to be included in the system as well as how they are connected. This facilitates the understanding of the system. The initial flowchart is also the basis for the next phase of the LCA, the inventory analysis, where data is collected for each process in the chart (Laurent & Hauschild, 2015).

There are four main options to define the system boundaries:

- Cradle to Grave – includes the material, energy, and all processes from the raw material extraction through the production, transportation, and use phase up to the product's end of life treatment.
- Cradle to Gate – includes all processes from the raw material extraction through the production phase (gate of the factory); used to determine the environmental impact of the production of a product.
- Gate to Grave – includes the processes from the use and end-of-life phases (everything postproduction); used to determine the environmental impacts of a product once it leaves the factory.

- Gate to Gate – includes the processes from the production phase only; used to determine the environmental impacts of a single production step or process (Pålsson & Riise, (2011)

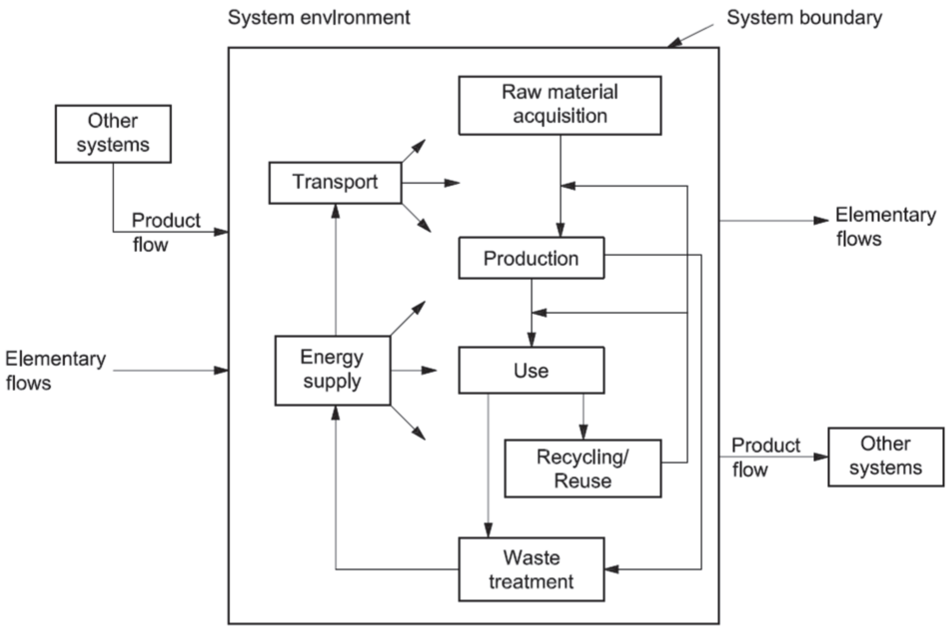

Figure 3. Process Flow Diagram

3.1.1.5 Data Quality Requirements

The usefulness and reliability of the results from an LCA study depend on the quality of the data that is used and the extent to which data quality requirements are met. It needs to be defined what data that should be collected, and how and where the data should be collected. Therefore, it is important to define the level of data quality that is needed to fulfil the goal of the study (Hauschild et. al., 2018).

As stated in the ISO 14044 (2006), the data quality indicators important for this phase include but are not limited to the following: First is the measure of the variability of the data values for each data category expressed. Next, the degree to which the data set reflects the true population of interest should be considered. Thirdly, is the consistency of how uniformly the study methodology is applied to the various components of the analysis. Finally, it's important to evaluate the extent to which information about the methodology and data values is easily reproducible by a third party. Additionally, the desired age and the minimum length of time, the geographic area from which data for unit processes should be collected and the nature of the technology mix should be assessed (Hicks, 2010).

3.1.2 Life Cycle Inventory

The second phase of the LCA is the process of collecting quantitative and qualitative data for every unit process system related to the product. In most cases, this phase of the LCA will include a flow diagram of the activities being assessed that will accurately illustrate the inputs and outputs addressed in previous phases (LCA Food Database, 2012). The input and output data needed for the model are collected for all activities within the system boundary, inclusive of those from the respective supply chain (Hauschild et. al., 2018). Having understood the layout of the system as presented in the flow diagram, it is easier to begin the data collection process.

Typically, the data collection process requires a combination of research, site visits, and direct contact with experts. Alternatively, the use of a commercially available or open-source LCA software package may be necessary here. According to the JRC Technical Report on LCA (2016), the following four steps are necessary to achieve a well-conducted life cycle inventory:

1. Develop a flow diagram of the processes being evaluated.
2. Develop a data collection plan.
3. Collect data.
4. Evaluate and report results.

There are two approaches typical with life cycle inventory based on UNEP/SETAC guidance on LCA (UNEP 2011):

a. Attributional approach - Attributional modelling makes use of historical, fact-based, measurable data of known systems and includes all the processes that are identified to relevantly contribute to the system being studied. It is a system modelling method whereby inputs and outputs of a product system are assigned to the functional unit by connecting or dividing the system's unit processes according to a standardized rule. For background data, producer-specific LCI data is ideally used where specific producers provide a background good or service. Average or generic data is typically used where the products and services are from a wide mix of producers or technologies.
b. Consequential approach - It is a method of system modelling whereby activities in a product system are connected in such a way that the activities in the product system are included to the degree that they are expected to change because of a change in the functional unit. According to Consequential-LCA (2020), this method addresses the environmental impacts related to those activities that are expected to change when producing, consuming, and disposing of the product. Thus, the purpose of consequential modelling is decision support. This implies that in such a system, the outcomes are tracked into the future.

3.1.3 Impact Assessment

Life cycle impact assessment can be explained as a "quantitative or qualitative process to characterize and assess the effects of the environmental interventions identified in the inventory table" (Heijungs & Hofstetter, 1996). The essence of this activity is to translate the elementary flows compiled in the inventory phase to the potential environmental impacts they may contribute during the life cycle of the studied system (Hauschild, et. al., 2015). This will help provide answers to the questions posed in the goal definition of the study and support decision-making.

This phase of the life cycle assessment consists of five steps; three mandatory steps and two other optional steps as identified in ISO 14044 (2006). The first step is to figure out which impact categories exist. Then the LCI result is then assigned to applicable impact categories, either on a case-by-case basis or by defining a default list of impact categories, with a distinction made between each category (Guine´e, 2015). Secondly is the classification step, in which each LCI result is assigned to the selected impact category relevant for the LCI result. Finally, the characterisation phase involves multiplying the category indicator results by a characterization factor and aggregating all of the findings within the same impact category to provide a numerical indicator result. Additional but optional steps which can be included are "normalization" and "weighting."

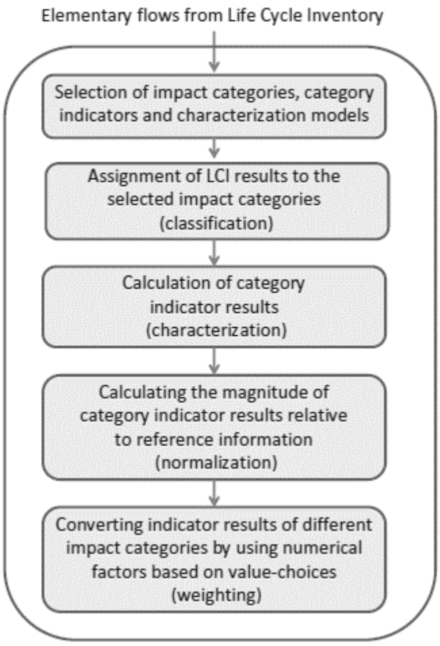

Figure 4. The five steps of life cycle impact assessment. *Adopted from Hauschild (2018)*

3.1.4 Life Cycle Interpretation

This is the phase where the results of the three previous phases are verified, quantified, analysed, and evaluated. It comprises a final report that explains the major issues discovered during the process, the study's limits, a set of conclusions, and an overall interpretation. Also, this is not just present results, but to make assertions as to the confidence level of the recommendations. Therefore, the correctness of the evaluation, the sensitivity of the data, and the completeness of the investigation must all be reflected in the results (ISO 14044, 2006).

3.2 Data collection Strategy

Due to the inability to carry out site visits to the production facility of pre-insulated DH pipes, data was primarily collected through a custom-made questionnaire and interviews administered to a cross-section of the major pre-insulated pipe manufacturers across Europe addressing a series of questions ranging from the manufacturing process of pre-insulated, raw and intermediate materials input, waste generation and handling, and energy consumption amongst others within the production facility every year. In total, twenty (20) companies were contacted with nine (9) responses received out of which only five (5) completed the questionnaires fully. The full questionnaire is available in **Appendix 1**. Furthermore, follow-up interviews were conducted with two (2) of the respondents to elaborate and get more insights into the feedbacks from their respective responses. As recommended in the ISO 14044 (2006), where the data is unavailable, insufficient, or deemed unusable, relevant literature where similar studies were carried out was consulted.

Technical information about the main components of the pipe like material types and quantities (mass) is based on the product catalogue from manufacturers such as the Logstor Product Manual v.2020.03 (2020) and feedback from producers. Energy consumption is based on the answers given in the questionnaires and interviews. The processes behind the inputs and outputs have been based on generic datasets from GaBi Education database. Microsoft Office Excel spreadsheet application was used to handle and organize data before impact assessment, and to generate presentable tables and figures. Thereafter, GaBi Education v2.1 LCA software preinstalled database was used to analyse and compute the impact assessments. This is a tool is that provides an easily accessible and constantly refreshed content database that details the energy and environmental impact of sourcing and refining of raw material or processed components of a manufactured item. The GaBi assessment tool supports a large amount of data and provides solutions related to process optimization, environmental criteria, and external representation of results (GaBi, 2011). However, the use of GaBi and ReCipe was not without accompanying challenges. The main shortcoming of the tool is its complexity.

4.0 COMPARATIVE LCA OF DISTRICT HEATING PIPES

4.1 Goal and Scope of the Study

The goal of this study is to benchmark a new PET insulated district heating pipe against the state of the art: bonded PU pre-insulated pipe. It aims is to investigate whether PET foam insulated pipes have the potential to favourably compete and possibly replace traditional PUR foam insulated pipes from a circular economy perspective.

This study will help to compare the environmental performance and impacts of the products to be analysed. It is possible for the outcome of this study to serve as part of a guide for decision-making authorities to determine the future of material flows within the district heating infrastructure setup and practices. In addition, researchers can hinge on the outcome of the study to further develop areas where further research may be required in a wider context.

This LCA considers the extraction of raw materials, the production of basic and intermediate products, and the assembly of the final product. It encompasses the production of the pipes from raw material acquisition to final production. The use phase is not considered because the thermal losses of the insulation materials are assumed equivalent.

4.1.1 Functional Unit

A functional unit is the basis of the comparison of an LCA. It provides a reference to which the inputs and outputs can be related and is closely related to the function carried out by the products to be investigated (Bjørn et al., 2015). Since the function of the pre-insulated district heating pipe is to transport heat energy to end-users throughout its lifecycle, for simplicity on the data collection and calculation, a length of pipe was selected. The functional unit of this study is "the production of a 2.42 m DN100 pipe"

After consulting product catalogues of major pipe producers around Europe like Isoplus (2019); Logstor (2020) and Uponor (2019), the specifications for the dimensions according to DN100 is identical, so for consistency, the Logstor Product Manual v.2020.03, (2020) was referenced during calculations throughout this study.

The technical specification of a standard steel pre-insulated pipe is given as follows:
Pipe length = 6m
Steel pipe diameter = 114.3mm (DN100)
Jacket pipe diameter = 200mm
Thermal conductivity of PUR foam = 0.027W/mK
Maximum continuous operating temperature = 90ºC

4.1.2 System boundaries

This LCA represents the cradle-to-gate approach. Cradle-to-gate is an assessment of a partial product life cycle from resource extraction (cradle) to the factory gate (gate). It includes each product system except for the use and end-of-life phases. This is the case because it is assumed that the impact of the use phase is equivalent as the considered pipe types are set to have the same insulating capacity, and as for the end-of-life scenario, interviews from practitioners revealed that this life cycle phase does not a true reflection since it is claimed that DH pipes are seldom unearthed after decommissioning. As a result, detailed information about disposal or recycling of decommissioned DH pipes is scarce or not sufficient.

The boundaries of the study include the following elements:

1) Raw materials acquisition – This phase will be limited to the extraction of the raw materials needed to produce only core intermediate materials required in the final production. Here, the processes of steel production, HDPE, aluminium foil, copper, and Electricity input.
2) Production of core intermediate materials – This will include production of the welded steel and the following:
    a) PUR foam – MDI, Polyols, electricity
    b) PET foam – virgin PET granulates, epoxy resin, catalyst, electricity
3) Transportation to the pipe production facility.
4) Production of pre-insulated DH pipes – At this phase is the coupling and assembling of manufactured raw materials and intermediate materials are into sections of finished pipes ready for dispatch. Accessories like spacers, surveillance copper wire, cleaning agents, machinery, fuelling, and electricity are factored in.

To ensure that the product system in this study is well addressed, emphasis is only placed on the material, energy, and activities that contribute directly to the production and performance of the system. Consequently, factors like machinery, maintenance of equipment and production facilities, heating, and lighting amongst others are excluded.

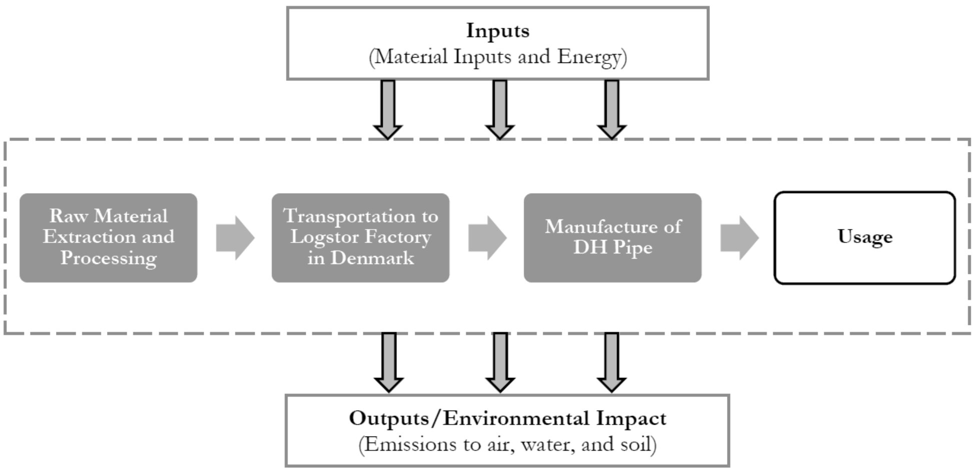

Figure 5. System Boundaries. *The shaded indicates the actual scope of the LCA*

4.1.3 Product System

Li, Zhang, Liu, Ke and Ating, (2012), characterized the product system of an LCA into two categories- Background System, where secondary data from databases, literature, public references, or estimated data are collected and Foreground System, where primary, site-specific data will be collected.

The Foreground System is also referred to as the Primary system since it entails the primary activities that contribute directly to the product's major life cycle phases. On the other hand, the Background System, otherwise known as the Secondary/Subsystem, includes supplementary materials and/or processes that relate directly to the primary activities.

The following were considered when setting up the system boundary and this is adopted from Ekvall & Weidema (2004):

a. Environmental Systems: Since products interact with external factors like material, energy, or information exchange throughout its lifetime, the origin of the material and energy going into the product from the environment, as well as the waste emanating from the material after use is important this LCA.

b. Components, Subsystems, and Services: The analysis of a product life cycle becomes easier when the sequence of operations associated with a product or material is broken down into primary systems and subsystems. Some of the constituents in the system may be third-party products undisclosed productions chains. In this case, it is necessary to include activities with a clear and direct tie to the system.

c. Geography: The impact of a system may vary depending on its geographical location throughout its lifetime. Thus, concerning geographical boundaries, one must decide what a reasonable area or distance from the system should be for a given scenario.

d. Time: Even though an LCA strives to measure the effects of the 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.

4.1.4 Allocation Procedures

Identification of the most appropriate allocation key is essential. The inputs and outputs of the system are partitioned between different products or functions in a way that reflects the underlying physical relationships between them, i.e., they reflect how the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system. Wherever possible, physical relationships are utilized to reflect meaningful shares of the burden (Aguirre-Villegas, et al., 2012). In this study, the allocation procedures used for the foreground processes are based on physical relation “Mass”.

4.2 Life Cycle Inventory Modelling

The Inventory step revolves around describing the different product systems, their function, characteristics, and life cycles. The attributional modelling framework has been applied in the LCI for this study. This choice was made because this LCA is focused on evaluating the potential environmental impact of existing processes and manufacturers, and since the objective is to also trace specific aspects of the product back to its contributing unit processes, which is usually the case in attributional modelling, this approach is therefore appropriate for this study.

The methodology for the LCI phase has included data collection, modelling of the different supply chains, and a calculation of the environmental impacts. The LCI was started with deciding which data sets were important to include in the study, after this the collection of data was initiated the last step of the LCI phase was to use the collected data to create models for the product system. During this process complementary inventory data was collected, both in terms of complementary site-specific data from the suppliers, but also general data for some of the inputs, such as in energy consumption. Since the LCI process is iterative, and several data collection have been delayed for different reasons, the steps of the LCI haven't been conducted in sequence but rather simultaneously, along with the collected data. All collected data and calculations are documented in tables in **Appendices 2 & 3**

4.2.1 Data Quality

Generally, data collected directly from core stakeholders during interviews and from the questionnaire are prioritized. To ensure the quality of the data, the following factors as explained by Environmental Protection Agency (EPA) publication on Guidance for Data Quality Assessment for Life Cycle Inventory Data (2016):

a. **Geographical Data Quality Goal**- As prescribed by ISO 14044, this is the geographical area from which data for a unit process is collected to satisfy the goal of the study (ISO, 2006b). The data in this LCA study are not case-specific but representative of the average European situation. Data relates to the current situation in Europe in terms of production techniques in operation and energy mix.
b. **Time-Related Data Quality Goal**- Time-related coverage considers the age of the data and the minimum length of time over which data should be collected. This allows a correlation to be established between the age of the data generation and the period of interest in a study. Therefore, data collected for this study are not older than 3 years (2019 at the oldest).
c. **Technological Data Quality Goal-** The technology process design refers to set conditions of a process that influence the final product. Here, great care is taken to ensure that processes are modelled to the best possible level of precision taking into consideration process design, operating conditions, material, and scale.
d. **Completeness Data Sources-** Concerning the source of background data, the GaBi database available in the GaBi software was used. GaBi Database has by far the largest LCI data industry coverage worldwide (Spera, n. d.). As a result, consistency in the input data is possible; especially for data types where the level of details to background processes are very limited.

4.2.2 System Description

This report examines two types of district heating pipe systems with equal functionality - PUR foam (Type A) and PET foam (Type B) insulated pipes. The studied pipes are single DN100 dimensions in both cases.

The Type A pipe is modelled after the Logstor steel pipe system - P235GH Welded - Series 1 as detailed in the Logstor Product Manual, Version 2020.09. Inside is the carrier pipe typically made of steel, then an insulating layer of polyurethane foam (PUR foam), that is specifically suited due to its insulation qualities. Afterward is a protective jacket of high-density polyethylene (HDPE) on the outside of the pipe, all bonded firmly together into a robust sandwich structure. (Logstor, 2020).

Structure of the pipe – Type A:

i. **Carrier pipe** - It is a prefabricated pressure pipe made of longitudinally or helically welded pipes in compliance with the EN10217-1, EN10217-2, and EN10217-5 standards
ii. **Insulation** – The pipe is insulated with polyurethane foam (PUR foam). Polyurethane has a lambda value of 0.022 at -20°C and 0.027 at +50°C. The PUR foam is produced from polyol, isocyanate, and cyclopentane. High-pressure plants are used for mixing and metering. The foam is homogenous and complies with the functional requirements of EN 253. PUR retains its mechanical properties for more than 30 years.
iii. **High Density Polyethylene** – The external jacket pipe is made with high density polyethylene (HDPE) material to protect the PUR insulator and ensure that the pre-insulated pipe can be exposed to underground conditions. Generally, polyethylene is resistant to weathering agents, UV-ray-proof, and capable of resisting chemicals and electrochemical interactions that occur in the soil.
iv. Specific stabilizers are used to assure the same initial thermal insulation features in the long term.

Plastic spacers are precisely positioned and are adequately suitable to resist the expanding forces of PUR during the injection foaming procedure.

Type B – The study of PET foam insulated pipes is hypothetical since it is not yet commercially available. Given this, the pipe structure is taken to be the same with Type A except for the insulation material, Since the energy efficiency of the system should be kept at the same level with the new pipes, the main assumption is that the heat losses of both pipes will be the same. Because the thermal conductivity of PET foam is higher than for PUR foam, the PET foam thickness has been calculated as to render the same pipe heat losses as the PUR insulated pipe. The calculation can be found in **Appendix 3Bi**. The main raw material for PET foam production is virgin polyethylene terephthalate (PET) granulate (and recycled PET in a separate comparable model). Other components are talcum powder, chain extender, antioxidant, and heat stabiliser, all mixed with a twin-screw extruder to obtain a PET foam resin. Carbon dioxide is used as the blowing agent as is widely used in extrusion foaming technology (Mangs, 2005).

For both pipes, sheets of aluminium diffusion barrier is introduced. This is to shore up the insulation properties of the foam by preventing loss of the blowing agents (cyclopentane/carbon dioxide), thereby resulting in better insulation and reduced heat loss. (Mangs, 2005)

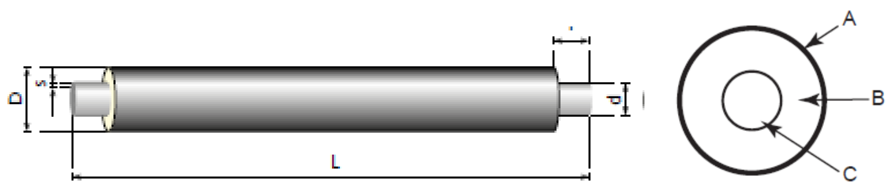

Figure 6. District heating pipe - A: Jacket pipe, B: Insulation, C: Carrier pipe
Source: Logstor Product Catalogue Industry, 2022

Table 2. Product System summary

	PUR foam-Insulated Pipe DN100	PET foam-Insulated Pipe DN100	Data Source	References
General				
Total Length as per functional unit (m)	2.43	2.43	Calculated	Section 4.1.1
Unit Weight (kg)	30,53	39,75	Calculated	Appendix 3
Outer Diameter (mm)	200	302.32	Product Catalogue	Logstor (2020)
Expected Service Lifetime (years)	30	30	Product Catalogue	Logstor (2020)
Carrier Pipe				
Material	Steel	Steel	Literature	Fröling et al. (2004)
Weight per Unit Pipe (kg)	23,86	23,86	Calculated	Appendix 3Ai
Outer Diameter (mm)	114.3	114.3	Product Catalogue	Logstor (2020)
Thickness (mm)	3.6	3.6	Product Catalogue	Logstor (2020)
Insulation				
Material	Polyurethane foam	Polyethylene terephthalate foam	Literature	Fröling et al. (2004)
Blowing Agent	Cyclopentane	Carbon dioxide	Literature	Fröling et al. (2004)
Weight per Unit Pipe (kg)	3.86	11.59	Calculated	Appendix 3Aii & 3Bii
Thickness (mm)	40.85	92.01	Calculated	Appendix 3Aii & 3Bii
Jacket Pipe				
Material	HDPE	HDPE	Literature	Fröling et al. (2004)
Weight per Unit Pipe (kg)	2.81	4.30	Calculated	Appendix 3Aiii & 3Biii
Thickness (mm)	2	2	Product Catalogue	Logstor (2020)
Surveillance				
Material	Copper	Copper	Product Catalogue	Logstor (2020)
Size (mm^2)	3	3	Product Catalogue	Logstor (2020)
Weight per Unit Pipe (kg)	0.57	0.57	Calculated	Appendix 3C
Diffusion Barrier				

Material	Aluminium Foil	Aluminium Foil	Product Catalogue	Logstor (2020)
Weight per Unit Pipe ([kg)	0.38	0.61	Calculated	Appendix 3Di & ii
Waste at plant (%)				
Steel	0,30	2.91	Calculated	Appendix 3Ei
HDPE	0,04	0,06	Calculated	Appendix 3Eii
PUR Foam	0,48		Calculated	Appendix 3Eiii
PET Foam		0,23	Calculated	Appendix 3Eiv

4.2.3 Life Cycle Phases

4.2.3.1 Raw Material Extraction and Refining

This part of the report will only concentrate on the core components of the pipes including how and where they are sourced from. This limitation is because of the seemingly endless number of materials and processes contained within this section of the LCA holistically. It implies a distinction between acquiring and processing raw materials and the actual production of the pipes. All data concerning raw material extraction and refinement has been defined as non-specific and has therefore been collected from the LCA inventory databases in GaBi. The locations mentioned as the source of the materials are obtained from a similar report to this study by Olsson, 2020. The location of the production site for this LCA has been taken as the Logstor production facility in Denmark. This is due to the reason that available data for this phase in the LCA relates directly with Logstor. It is also necessary to note that the PUR foam mixture as well as the extrusion of the PET foam is carried out within production facility to ensure standardisation of quality.

4.2.4.2 Steel – Carrier Pipe

According to feedbacks from respondents and interviews conducted with pipe producers, the DN100 steel carrier pipes is commonly used among manufacturers, although in some cases it can be tailored to the client's specification and sourced mainly from Cremona, Italy.

As described by the Association of Iron and Steel Technology (2021), steel production involves different phases ranging from the production of pig iron, production of liquid steel, hot rolling and/or cold rolling, applying a metallic and/or organic coating. The process of steel production begins with the extraction of three major iron components; iron ore, coke, and lime, which are fed into a blast furnace to generate molten iron. One portion of the iron ore is converted into iron pellets, while the other part, together with the limestone, is converted into a sinter. Coal is converted into coke, which is the primary fuel source in the blast furnace. Pig iron is made by combining sinter, coke, pellets, and lime at a high temperature of about 1600 °C. Molten iron is sometimes combined with recycled steel scrap and treated in a basic oxygen furnace that melts scrap steel.

During the secondary refining operations, the molten steel is formed to exact chemical compositions. The refined steel is then typically cast into a range of solid forms using a continuous casting technique. Various procedures, like hot rolling, cold rolling, annealing, and coating, are used to transform the solidified forms into final products (World Steel Association, 2020).

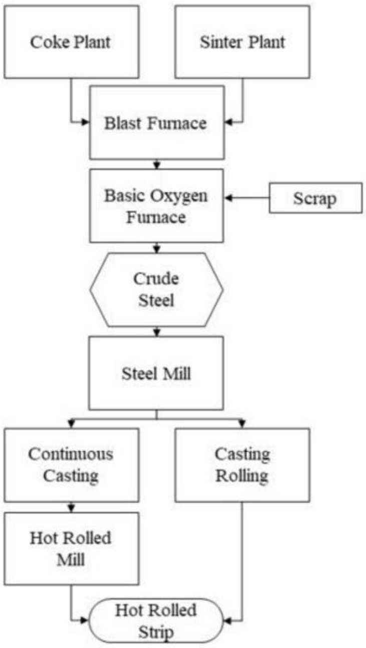

Figure 7. Steel production process. Source: Backes et al., (2021)

4.2.4.3 High Density Polyethylene (HDPE)

HDPE is the main material of the jacket pipe in the product system and is shipped from Vienna, Austria. It is a rigid and durable material that offers greater chemical resistance with high melting point (135°C) that allows it to withstand higher operating temperatures (wkmounts, 2020). Its more crystalline structure also results in greater strength and opacity of the material, which makes it commonly used in piping systems (Azeem, 2009). HDPE is produced by either altering natural gas (a methane, ethane, and propane blend) or catalytically breaking up crude oil into gasoline (Lepoutre, n d.). When crude oil is heated under the appropriate circumstances, it emits ethylene gas, which is collected and stored. This process is often known as "cracking." During the manufacturing process, the gas molecules will attach to create polymers, which will subsequently generate polyethylene. Polyethylene is first a heated, sticky pulp that is forced through small pores and chopped with a spinning knife to create solid pellets the size of relatively big hail (Scanton, 2017). **Figure 8** describes a general polyethylene production process.

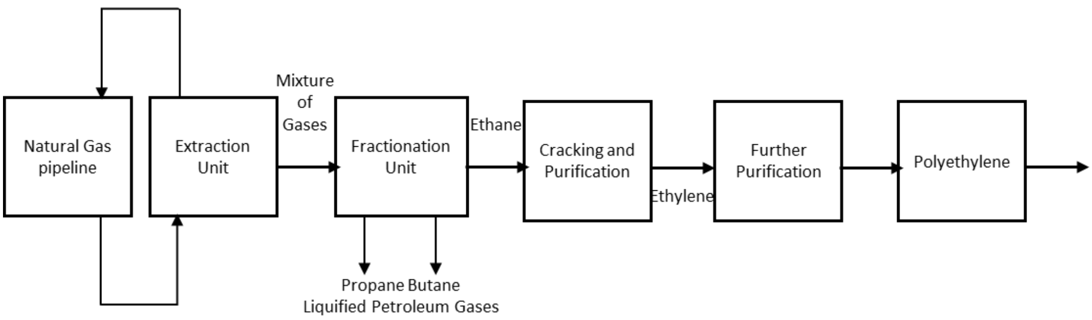

Figure 8: Diagram of the polyethylene production process from liquified petroleum gas. *Adapted from: (LyondellBasell, n. d)*

4.2.4.4 Insulation – Polyurethane and Polyethylene Terephthalate Foams

Polyurethanes are traditionally and commonly formed by reacting diisocyanates with polyols.

a. **Diisocyanate** – This is an organic molecule containing two isocyanate groups. They are one of the most important reactive ingredients used in the production of polyurethanes. Toluene diisocyanate (TDI) and methylenediphenyl diisocyanate (MDI) are the commonly used types. TDI is made by putting nitrogen groups in toluene, reacting them with hydrogen to make a diamine, and then separating the unwanted isomers. It is used mainly for the production of flexible foam. To produce MDI, a phosgenation reaction of aniline-formaldehyde polyamines is carried out (Six & Richter, 2005). It is mainly sourced from Lemförde, Germany.
b. **Polyols** – Just like diisocyanate, polyols are sourced from Lemförde, Germany. It's a chemical that include several alcohol groups (OH), are the other reactive species required to make polyurethanes. For this purpose, the polyether polyols that emerge from cyclic ethers are commonly used. They are high molecular weight polymers that have a wide range of viscosity. Normally, they are produced using the process of alkylene oxide polymerization (Ammar, 2020)
c. **Polyethylene Terephthalate (PET) granulates (virgin)** – This material forms the main component in the production of PET foam shipped from Leipzig, Germany. PET is basically produced by polymerization of ethylene glycol and terephthalic acid which are by-products from the refinement of crude oil and natural gas (Scanton, 2017). These substances are combined to form long chains of molecules. In this process, the starting molecules consisting exclusively of carbon, oxygen and hydrogen are attached to one another by so-called ester bonds. At the end of the polycondensation, you obtain a viscous molten mass, which is pressed into thin threads, cooled, and reduced to granules (Zein et al., 2010).

4.2.4.5 Aluminium Foil

The aluminium foil serves the purpose of the diffusion barrier that helps to retains the cyclopentane and carbon dioxide in the insulation and also prevents nitrogen or oxygen from soil or water from penetrating. For the purpose of this study, it is gotten from Horsens, Denmark.

According to the European Aluminium Foil Association (2021), aluminium is the third most prevalent element in the earth's crust after oxygen and silicon. It is derived from a mineral known as bauxite. There are two methods required to get pure aluminium from bauxite. The ore is first processed to remove impurities such as iron oxide, silica, titania, and water. The resulting aluminium oxide is then heated to get pure aluminium.

Alternatively, the ore is processed to produce alumina. The aluminium metal is then created from alumina by running an electric current across it in a process known as 'electrolytic reduction.' The resultant silvery metal serves as the foundation for a broad range of alloys, which are created by adding tiny quantities of other metals to offer the precise properties required for each application. The metal is then rolled to make foil. It is first produced by rolling heated lumps (ingots)to coils of thickness between 2mm and 4 mm. The coils are then successively cold rolled to the required foil thicknesses. Another method is to directly roll molten metal into a thick strip, which is then immediately rolled into the coil from which the foil is formed.

4.2.4.6 Copper Wire - Surveillance

Copper is sourced from Chybie, Poland. The surveillance system is mainly made up of the copper wire embedded within the insulation. For the benefit and safety of both people and the environment, this surveillance helps reduce damage, has a preventative effect, and extends the network's service life.

Pure copper is rare in nature and is usually found in the form of copper ores in conjunction with other chemicals. It is usually recovered from 0.5 to 2.0 percent copper oxide and sulphide ores. Processing copper is a multi-phase, time-consuming, and laborious process. Compounds commonly used in copper processing and refinement include sulfuric acid, oxygen, iron, or silica, depending on the technique and the type of ore (International Copper Study Group, 2016).

Copper ore is mined from open pits and must be crushed as part of the process between extraction and manufacturing. Copper ore is collected from the mine using today's compact mining equipment. After crushing, the ore is roasted, which aids in the conversion of sulphides to oxides. The oxides are melted to create matte, which is subsequently refined through a series of steps (Jacobs, 2018).

As described by the International Copper Study Group (2016), to reach high levels of concentration, copper oxide ores go through a three-step procedure. To begin, sulfuric acid is used to extract copper from the ore in a process known as heap leaching. Following that, the solvent extraction phase removes impurities from the copper by transferring it from the leach to a solvent. Finally, electrowinning uses an electric current to positively charge copper ions in a solvent, allowing them to be plated onto a cathode rod. The rod is dragged through a sequence of dies to get the final dimension of the desired copper wire, with the diameter of the rod decreasing with each pass-through.

Table 3. Inventory data of Raw Materials.

Component	Quantity (tonne)
Steel Carrier Pipe	288-350 units
Virgin PET Granulate	1
HDPE Granulate	20 - 25
Copper Wire (Steel)	1.9
Aluminium Foil	18
Cyclopentane	15 - 20
Isocyanate	22 - 26
Polyol	21.96

Adopted from Olsson, 2020

4.2.5 Transportation of Raw Material to Production Site

As previously stated, raw materials used in the pipe manufacture are shipped from different countries across Europe to the Denmark facility. Components are transported in trailer-truck Euro 4, 34 - 40t gross weight, 27t payload, or 33-EURO pallets capacity, while chemical components are transported in a tank truck. Using the respective sizes of components and the distances travelled, the emissions that occur through transportation are modelled. The trucks are taken to be diesel-powered. **Table 4** below presents details of parameters included in the transportation phase.

Table 4. Inventory of transportation and materials component to the production site.

Raw Material Component	Means of Transportation	Source	Travel Distance (km)
Steel Carrier Pipe	Truck	Cremona, IT	1,630
PET Granulate (virgin)	Truck	Leipzig, DE	810
PET Granulate (recycled)	Truck	Hedehusene, DK	50
HDPE Granulate	Truck	Vienna, AT	1,350
Copper Wire (Steel)	Truck	Chybie, PL	1,280
Aluminium Foil	Truck	Horsens, DK	150
Cyclopentane	Tank Truck	Algestrup, DK	380
Isocyanate	Truck	Lemförde, DE	650
Polyol	Truck	Lemförde, DE	650

Adapted from Olsson, 2020

4.2.6 Manufacturing of District Heating Pipes

The description of the pipe production explained in this report is in accordance with the general best practices of manufactures contacted for this study.

4.2.6.1 PUR-insulated pipe

Traditionally foamed insulated pipes are manufactured by injecting the insulating foam mixture between the carrier pipe and the jacket pipe. It starts at the extrusion line with the extrusion of the Jacket pipe. The essential steps of here is to heat, melt, mix and convey granulates into the desired pipe shape. Where a diffusion barrier is required, aluminium foil is attached to the pipes at this point.

At the same time, the steel is briefly heated and sandblasted. Next, is the process of positioning the steel pipe into HDPE casing with the help of spacers. Installation of centring parts and leak detection wires is done at this phase. Thereafter, PUR foam mixture (which is produced in another process) is injected in the cavity between the jacket pipe and the steel carrier pipe, which soon expands to fill up the void. After some time (approximately 30 mins) the foam hardens, to make up a strong adhesive between steel and HDPE pipes and insulates very well. It should be noted that the PUR foam is not supplied in its final shape to the production line. Instead, the chemicals are acquired separately and processed during the assembly of the DH pipes. As such, the inventory data is based on the chemical constituents.

In modelling the pipe manufacturing process, the coupling and assembling of raw materials and intermediate materials are factored in. Only the main materials that directly influence the production line (Steel pipe, HDPE casing, PUR foam mixture, copper wire, aluminium foil, spacers, cover and packaging) and energy use are included in the model of the pipe production. Energy consumption for each of the main processes is based on measurements and estimations provided from contacted manufacturers.

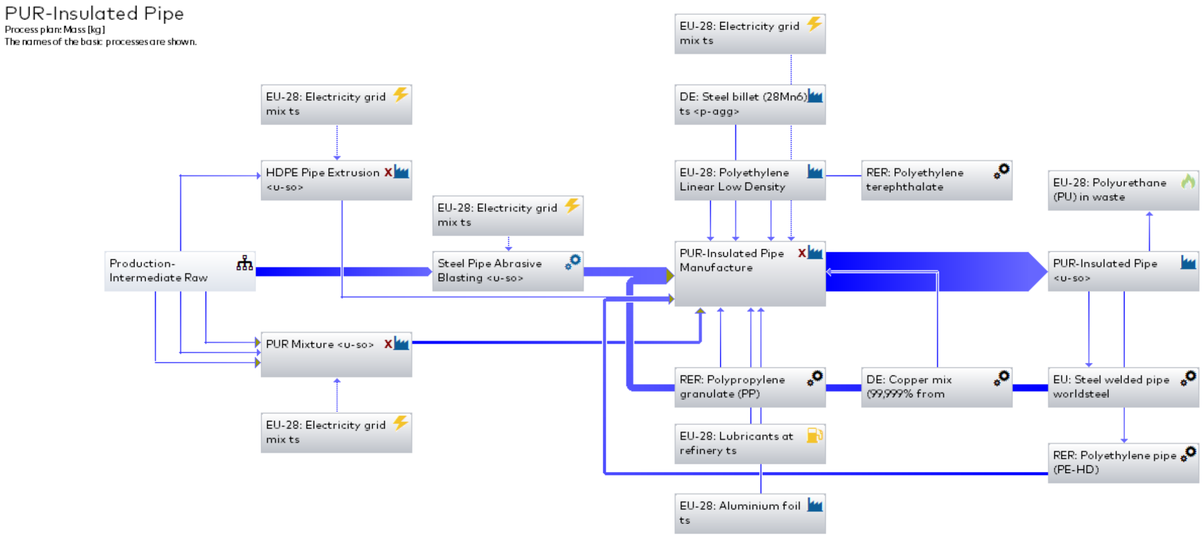

Figure 9. Flow diagram of PUR-Insulated Pipe production

4.2.6.2 PET-insulated pipe

The production components of PET-insulated pipe is assumed the same as PUR-Insulated pipe, except for the production of the PET foam, which is carried out by extruding the foam around the steel carrier pipe before the jacket pipe is then attached. Details about the production of PET foam are taken from the patent filing of Armacell (Meller, Li & Dolega, 2012) and summarized in a separate section.

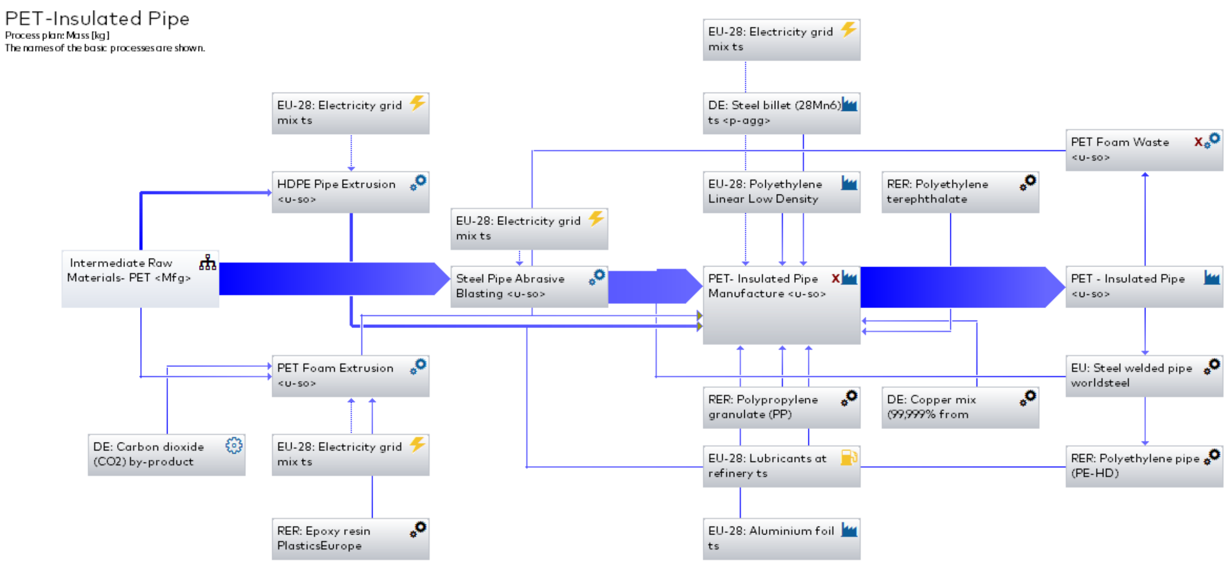

Figure 10. Flow diagram of PET-Insulated Pipe production

4.2.7 PUR Foam Mixture

The core ingredients in the manufacture of a polyurethane mixture are diisocyanates and polyols (Pinto, 2010). Irrespective of the finish-product, the manufacturing process is the same. It involves measuring liquid isocyanate and resin blend at a specified ratio and mix them till a homogeneous blend is obtained. The resulting solution is either sprayed or injected into a mould and left to rest till it solidifies. (Howard, 2002)). In addition to TDI, MDI, and polyols, other chemicals like catalysts, surfactants, pigments, etc which are usually added in small amounts (typically less than 1 to 2%) are also used in producing polyurethane (Boustead, 2015).

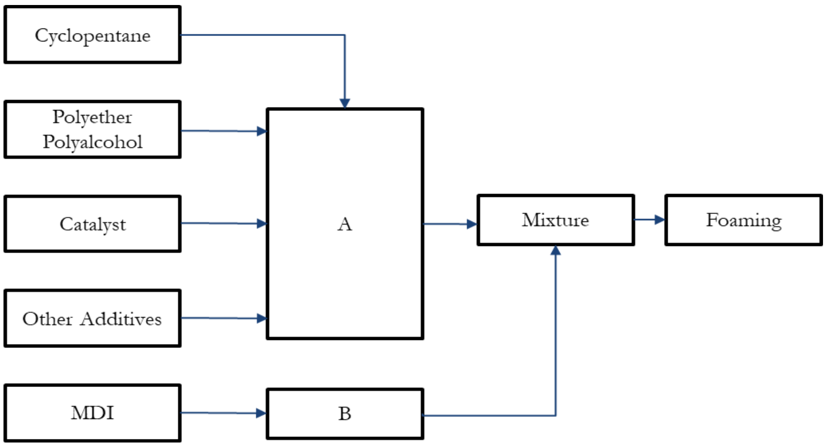

Figure 11. Sequence of operation for PUR foam production. *Adopted from Jiang, et al, 2015*

Table 5. Weight composition of materials in PUR foam production

PUR Components	% Weight
Polyol	48.43
Pentane	1.14
MDI	48.43
Surfactants	1.5
Catalyst	0.5

Adapted from Borreguero et al., 2010

4.2.8 Extrusion of PET Foam

According to the patent application document (Meller, Li & Dolega, 2012), the production of a PET foam material comprises of weighing PET, chain extender, antioxidant, and nucleating agent. After which, PET granulates is vacuum dried at high temperatures of up to 140° C for 12 hours, while the chain extender, the antioxidant, the nucleating agent, and the heat stabilizer are also vacuum dried at 80°C. for 8 hours. The components are mixed in a high-speed mixer for 10 minutes, and then putting into a foaming extruder. Controlling the heating conditions of the foaming extruder and the speed of the screw, a foaming gas (carbon dioxide) is fed at a rate of 0.5 to 3 kg/hr for foaming.

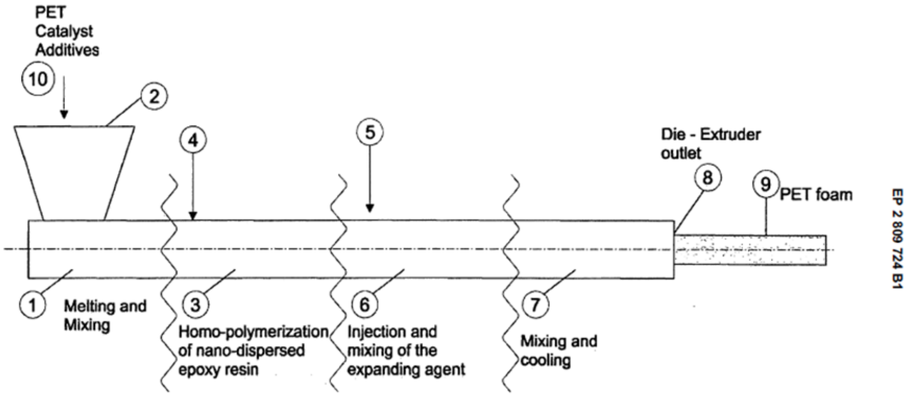

Figure 12. Production of PET foam (Lindenfelzer, et al., 2011)

Table 6. Weight composition of materials in PET foam production

Components	% Weight
Virgin PET granulates	95.0
Chain Extender	2.5
Nucleating Agent	2.0
Stabilizer	0.5
Foaming Agent	CO_2

Adapted from: Patent Application Publication - (Meller, Li & Dolega, 2012).

4.2.9 Energy Consumption

The energy consumption data presented in **Table 7** is the weighted average of the feedbacks received from contacted district heating pipe manufacturers across Europe via the questionnaire and interview. The average annual electricity consumption in the production line and pipe output is 24,221,586 KWh and 10,000 tons of pipe respectively. This value has been scaled down and interpolated to satisfy the functional unit of this study. This approach is applied to both PUR and PET-insulated pipes.

Table 7. Electricity consumption at production

	Referenced Weight (kg)	KWh as per Referenced Weight
PUR-Insulated Pipe	30.53	7,39
PET-Insulated Pipe	39.75	9,63

4.2.10 Waste Management in Production Line

When evaluating the long-term viability of a manufacturing process or organization, waste is an important consideration. In this product system, waste management within the production line was modelled to be handled in two main ways: either by incineration and or by reuse. The complete scrap percentage on all products is approximately 0,9%. This percentage covers the main raw material groups Steel, PUR chemicals (Polyol and Isocyanate), and HDPE casing. PUR foam is not recycled but is sent to an incineration plant where they are burnt under controlled conditions and produces electricity and District Heating water. Up to 95% of steel scrap and off-cuts are recycled by companies that are specialized In recycling steel scrap. 80% of HDPE waste is recycled and reused in the production of new pre-insulated pipes. The remaining part is sent to an incineration plant where they will burn it under controlled conditions to produce electricity and District Heating water. Pet foam is assumed to be reused in the production process.

4.2.11 Assumptions

1. The process of recycling scrap from the steel pipe, jacket pipe and the PET foam before they are reintroduced into the system, as well as the energy consumed in this process was not included. Only material quantity was considered.
2. The assumption is only the data of mass input/output, amount of energy input/output, amount of emissions and waste produced is used to analyse the life cycle assessment. The Life cycle inventory used is from the GaBi software.
3. The location of the production facility, origin of the raw materials, electricity, and energy was not prioritized, only the balance of the system is taken into account in an average European value.
4. Materials representing which are less than 0.5 percent by weight of the pipe and are not included as these would have a negligible influence on the LCI results. Machinery used in the manufacturing phase as well as their maintenance are also excluded from the analysis.

4.3 Life Cycle Impact Assessment (LCIA)

The LCIA stage of an LCA addresses the evaluation of environmental impacts of products and services over their whole life cycle. This is accomplished using LCIA methodologies, which classify emissions into impact categories before characterizing them to common units for comparability (EU ILCD, 2010).

4.3.1 Life Cycle Impact Assessment Method

In evaluating the environmental impact assessment, the ReCipe (2016) method was used. This method is common amongst researchers because it combines the indicators used in both CML and Ecoindicator 99. In this study, however, only the midpoint level indicators which represent the potential primary environmental impacts are implemented. The endpoint level indicators are excluded as it is capable of extending the scope of the study beyond what has been previously defined. Therefore, the midpoint level is deemed sufficient.

Furthermore, relevant categories were identified by ignoring those that are cumulatively less than 10% of the sixteen (16) weighted impact categories according to ReCiPe. The selected categories that sufficiently satisfy the aim of the study are considered. These are limited to include the following nine impact categories: Climate Change, Fossil depletion, Water depletion, Freshwater eutrophication, Human toxicity cancer, Natural land transformation, Marine eutrophication, Photochemical Ozone Formation, Terrestrial acidification. To get a better understanding, **Table 7** describes each category in detail.

Table 8. Selected Life Cycle Impact Assessment Method - ReCiPe

Impact Category	**ReCiPe Midpoint (H) Indicator**	**Unit**	**Description**
Climate Change	Climate Change	Kg CO_2 eq.	Climate change is the warming of the climate as a result of human activity. The main contributor and only climate forcing agent currently evaluated in life cycle impact assessment (LCIA) approaches is greenhouse gas (GHG) emissions, which produce an increase in radiative forcing. (Greendelta, 2015). The direct result is an increase in atmospheric and oceanic temperature, which causes a variety of higher-level impacts such as sea level rise, extreme meteorological events, and rainfall fluctuations, all of which harm human health and ecosystem quality (Goedkoop et al., 2009).
Abiotic Depletion	Fossil depletion	Kg oil eq.	This category's major focus is human and ecosystem health, and how it is impacted by the exploitation of minerals and fossil fuels, which are system inputs (Dincer, Colpan & Kizilkan, 2018). Fossil fuels refer to all resources that contain hydrocarbons such as coal, oil, and gas. The midpoint characterization and classification factors used in the ReCiPe 2008 method are expressed in oil equivalents.
Water Consumption	Water depletion	m^3	Indicator of the relative amount of water used, based on regionalized water scarcity factors. It explains the decline of quantity or quality of water resources. It is described as water that is not immediately available after it has been utilized. The water can either be incorporated into the product or evaporated into the atmosphere, depending on your preference. Non-evaporative water is defined as water that has not evaporated (Greendelta, 2015).
Eutrophication	Freshwater eutrophication	Kg P eq.	Eutrophication is the process of increased biomass generation in a water body as a result of higher plant nutrient concentrations (Rockström et al., 2009). Nitrogen (N) and phosphorus (P) emissions are two of the most significant sources

			of eutrophication since they are the chemicals that restrict the production of aquatic biomass (Nasir & Mohammad, 2014).
Human toxicity cancer	Human toxicity cancer	kg 1,4-DB eq.	Human toxicity refers to the carcinogenic effect of hazardous substances on human health when a unit of chemical is released into the environment. It is based on a compound's inherent toxicity as well as its possible dose. A typical example is during the burning of fossil fuels, by-products like arsenic, sodium dichromate, and hydrogen fluoride are produced in large quantities. When inhaled, consumed, or just come into contact with certain substances, they can be dangerous to humans (Greendelta, 2015).
Land Use	Natural land transformation	m^2a	In ReCiPe 2008, the land use impact category refers to damage to ecosystem caused by the effects of land occupation and alteration. Different areas have different spices diversity and not all types of occupation have the same effect on biodiversity (Goedkoop et al., 2008).
Eutrophication	Marine eutrophication	Kg N eq.	Excess nutrients cause plants and algae to grow explosively during the occurrence of marine eutrophication, disrupting the regular functioning of aquatic ecosystems (EC-JRC, 2010). Nitrogen is the essential nutrient in marine waters. The ReCiPe 2016 method characterisation and classification variables are based on nitrogen equivalents for marine eutrophication (Goedkoop et al., 2009).
Photochemical Oxidation	Photochemical Ozone Formation	kg ethene (C2H4) eq.	Eutrophication (also known as nitrification) refers to the effects of high amounts of macronutrients in the environment because of nutrient emissions into the air, water, and soil. (ecoinvent, 2019). This environmental impact entails the generation of ozone at the troposphere's ground level is induced by photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) and sunshine. By reacting with organic compounds, high quantities of ground-level tropospheric ozone harm flora, human respiratory tracts, and artificial items (Preiss, 2015).

Terrestrial acidification	Terrestrial acidification	Kg SO_2 eq.	The atmospheric deposition of inorganic substances such as sulphates, nitrates, and phosphates cause changes in soil acidity. For almost all plant species, an ideal level of acidity has been determined. When there is a large departure from this ideal level, acidification occurs, which is harmful to the species. As a result, changes in acidity levels will cause changes in a species' distribution. (Goedkoop et al., 2009).

4.3.2 Life Cycle Impact Assessment Results

This section presents the aggregated results from the Life Cycle Impact Assessment for both PUR and PET-insulated pipes within all of the nine identified impact categories. The results have been grouped graphically according to the life cycle phases (Extraction, Transportation, and Manufacturing) as indicated in the life cycle inventory. The chapter also includes a sensitivity analysis of the processes. **Tables 9, 10, 11, 12 & 13** clearly show the emissions that occurred at different phases in the life cycle of the studied systems.

Table 9. Emissions from PUR-Insulated pipe raw material extraction and processing (Kg)

Components	CO_2	NO_2	NO_X	SO_2
Steel welded pipe	65.19	1.00E-04	0.93	0.09
Diisocyanate	14.81	1.00E-05	0.21	0.02
HDPE granulate	9.05	0.17	3.00E-04	0.02
Polyol	0.07	1.10E-04	0.02	1.44E-04
Aluminium Foil	7.59	1.20E-04	0.13	0.63
Copper	2.03	0.04	3.30E-06	0.01

Table 10. Emissions from PET-Insulated pipe raw material extraction / processing (Kg)

Components	CO_2	NO_2	NO_X	SO_2
Steel welded pipe	65.19	1.00E-04	0.93	0.09
HDPE granulate	5.79	0.11	1.00E-02	0.02
Aluminium Foil	7.59	3.80E-01	0.13	0.063
Virgin PET granulates	0.33	0.01	1.96E-05	6.78E-04
Copper	2.03	0.04	3.30E-06	0.01

Table 11. Emissions from transport to production site (Kg)

	CO_2	NO_2	NO_X	SO_2
Transport to Logstor (PUR insulated Pipe)	155	0.17	0.04	0.05
Transport to Logstor (vPET insulated Pipe)	110	0.12	0.03	0.03

Table 12. Total Emissions to air resulting from Manufacturing (Kg)

	CO_2	NO_2	NO_X	SO_2
PUR-Insulated Pipe	116.54	0.11	0.69	0.63
vPET-Insulated Pipe	78.96	0.07	0.11	0.13

Table 13. Comparison of Life cycle Impacts - PUR foam pipe and vPET foam pipe

Impact Category	Unit	Extraction/Refinement		Transportation		Manufacturing		Totals	
		vPET-Insulated	PUR-Insulated	vPET-Insulated	PUR-Insulated	vPET-Insulated	PUR-Insulated	vPET-Insulated	PUR-Insulated
Climate change	kg CO2 eq.	952.00	1490.00	35.78	50.15	95.63	151.91	1083.41	1692.06
Fine Particulate Matter Formation	kg PM2.5 eq.	307.00	575.00	11.31	15.90	28.55	52.66	346.87	643.56
Fossil depletion	kg oil eq.	47.18	68.20	0.83	0.69	0.12	0.09	47.97	69.15
Freshwater Depletion	m3	0.00	0.04	0.00	0.00	0.00	0.00	0.00118	0.04
Freshwater Eutrophication	kg P eq.	7.68	11.70	0.01	0.01	0.92	1.24	8.61	12.95
Human toxicity, cancer	kg 1,4-DB eq.	22.30	54.50	1.67	2.34	1.65	2.20	25.62	59.04
Land use	Annual crop eq. yr	0.01	0.06	0.00	0.00	0.00	0.00	0.01	0.06
Marine Eutrophication	kg N eq.	1.39	2.35	0.26	0.37	0.14	0.23	1.80	2.95
Photochemical Ozone Formation, Ecosystem	kg NOx eq.	1.80	3.52	0.11	0.15	0.19	0.28	2.10	3.95
Terrestrial Acidification	kg SO2 eq.	952.00	1490.00	35.78	50.15	95.63	151.91	1083.41	1692.06

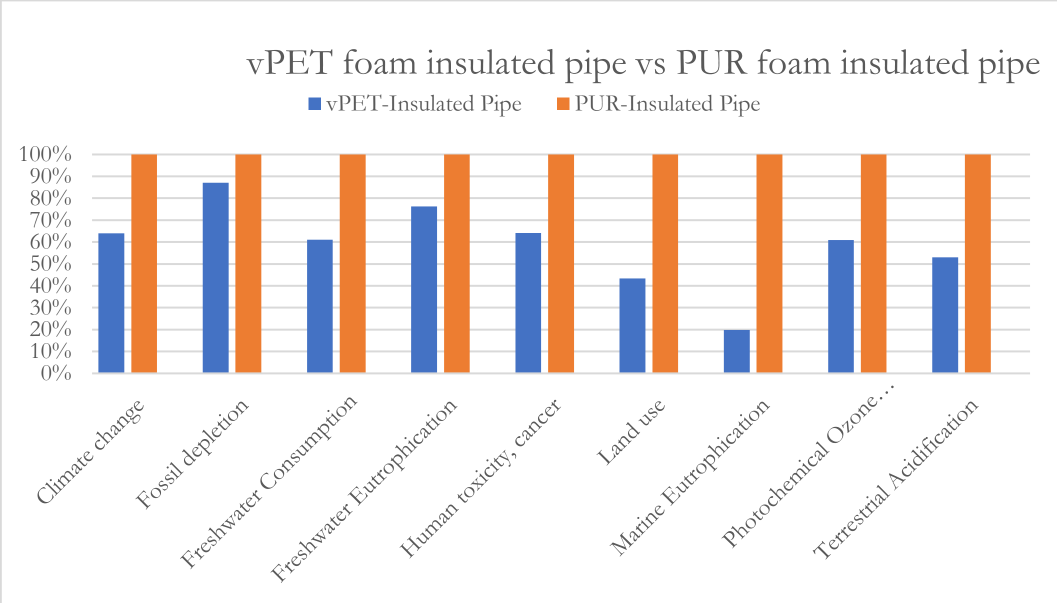

Figure 13. Characterized results of all impact categories for PET and PUR-insulated pipe. *Within each impact category, the pipe with the highest environmental impact is presented as 100% impact, and the other as a percentage of that value.*

As seen in **Figure 13**, the chart compares the potential environmental impact of the studied pipes. It can be observed that although PUR-insulated pipe consumes less materials than the PET foam insulated pipe, it has a higher potential impact across all selected impact categories. According to the weighting, the most significant impact categories are climate change, fossil depletion, freshwater consumption, and land use. Other impacts are noticeable but in very small amounts, but marine eutrophication is the least overall.

The main effects are determined by CO_2, NOx, NO_2 and SO_2 emissions, and the use of non-renewable resources in energy generation. This is particularly due to the extraction, refining, transportation, and use of fuels such as natural gas.

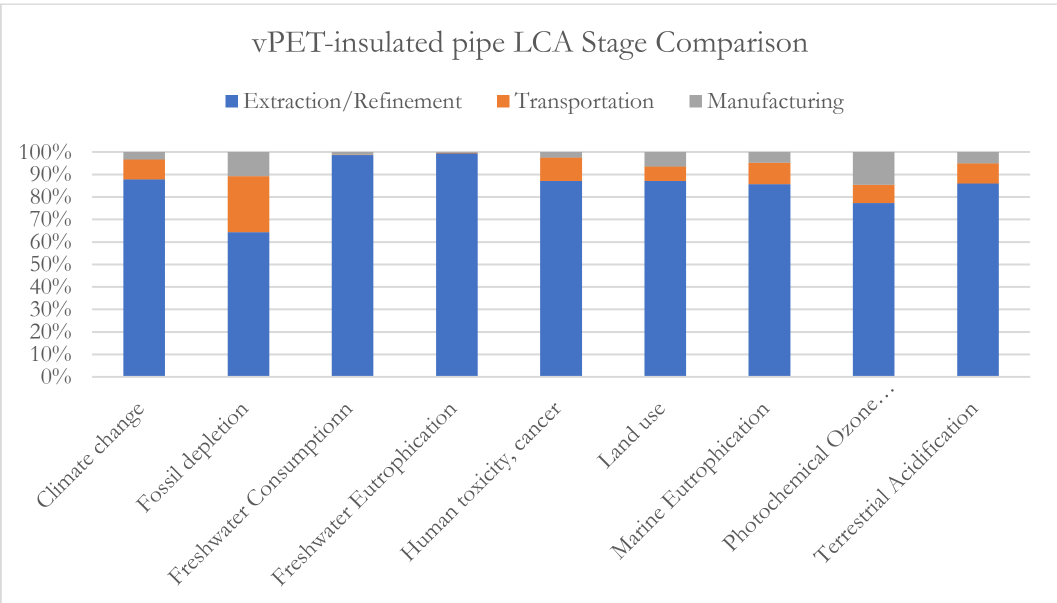

Figure 14a. Characterized results of all impact categories for vPET-insulated pipe

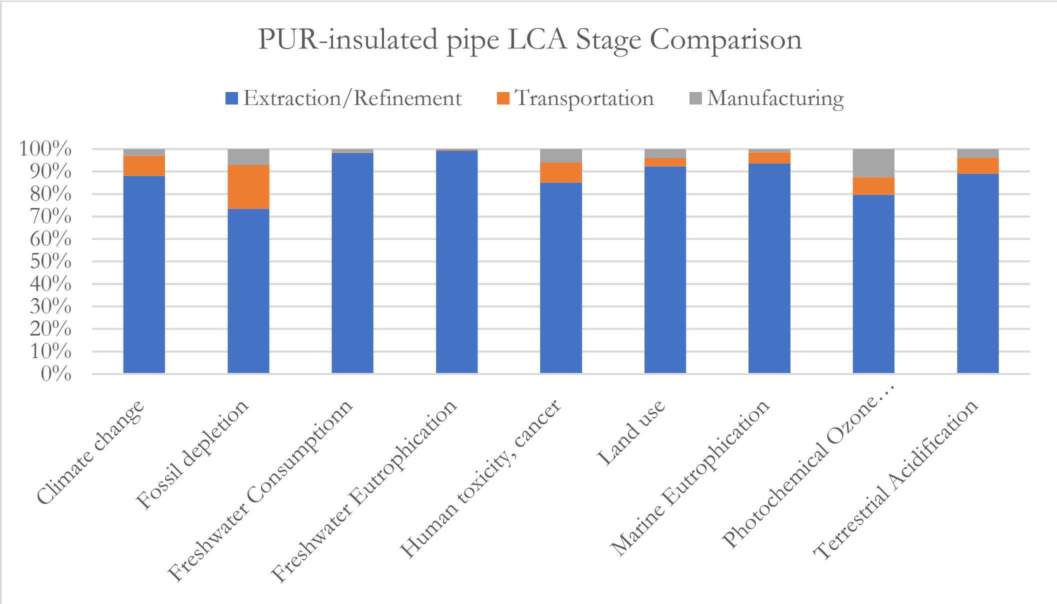

Figure 14b. Characterized results of all impact categories for PUR-insulated pipe

Figures 14a and **14b** explain the ratio between the two pipe types in terms of percentages. After all the phases have been analysed and compared, the area with most significant contributions, also known as hotspot, is seen to be the extraction and refinement phase. This phase, which also entails the production of intermediate raw materials, is found to account for more than 55% of environmental impacts in each respective category. This demonstrates that most of the impacts have already occurred before these materials are transported to the production facility. The Manufacturing phase also displays significant impacts. Moreover, it is necessary to point out that these impacts are mainly due to the energy consumption rather than the assembly of materials in the pipe even though it accounts for up to 95% of the total input. Conversely, the transportation phase is the least contributor within the system boundary with its total emissions responsible for less than 6% of the overall impacts combined.

4.3.2.1 Contribution Analysis of PUR foam Insulated Pipe

As part of the necessary steps to understand the role each individual material component in the environmental impact, a contribution analysis has been carried out. The outcome of this analysis may provide opportunities for redesign, prevention strategies.

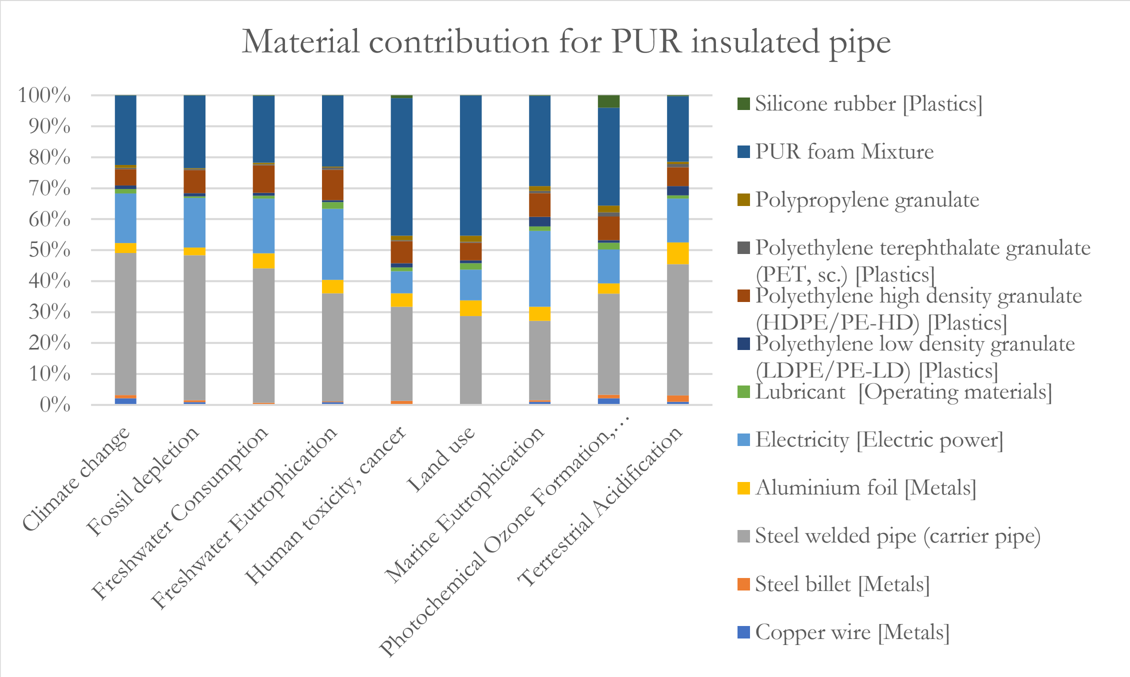

Figure 15. Material contribution analysis for PUR insulated pipe

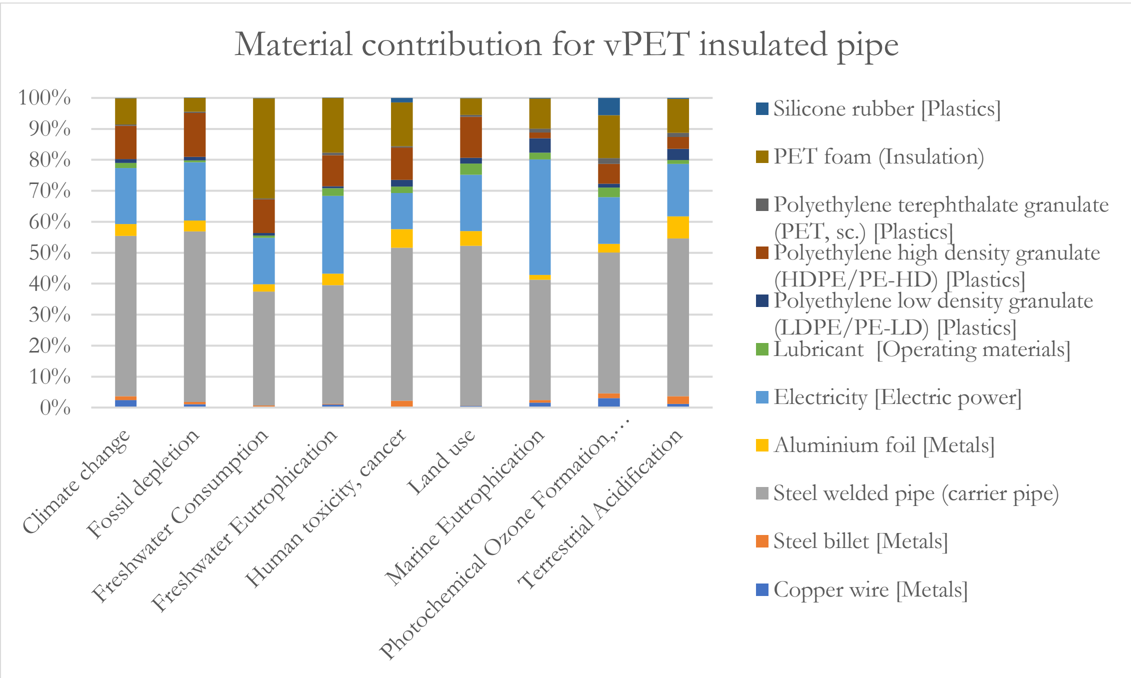

Figure 16. Material contribution analysis for vPET insulated pipe

The results show that most of the impact categories are dominated by the impacts related to the production of the core materials of the pipes. From the analysis presented in **Figures 15 & 16**, it is clear that the material components account for up to 80% of the environmental impacts posed by the product systems. Energy consumption accounts for the rest. The main contributors to this outcome in both cases are steel pipe, electricity, insulation, jacket HDPE pipe, and aluminium foil, but the steel pipe is the highest contributor in all impact categories. This is somewhat expected since the steel pipe alone is accounts for up to 78% of the total weight of the PUR insulated pipe and 60% of the PET insulated pipe. But in general, the contribution from each material is similar to the weight contribution but with the exception of aluminium foil, whose impact contribution are still noticeable despite the fact that they are less than 1% of the system.

For the PUR insulated pipe, asides the steel pipe, the PUR foam is predominant (about 29%) particularly in the Human Toxicity and Land Use impact categories, where the PUR constituents (MDI and Polyol) plays a key role. In the Climate Change, Fossil Depletion and Terrestrial Acidification categories, most of the impact here is shared between steel pipe, HDPE jacket pipe and the PUR foam due their high reliance on fossils for their production. When compared with the PET insulated pipe, the influence of the vPET foam is much lesser than PUR foam in almost all categories but for Freshwater Depletion.

4.3.2.1 Climate Change

According to the results for Global Warming, it is the largest impact category from the analysis of this LCIA. It is evident that the PUR-insulated pipe has the most effect on climate change particularly in the extraction/refinement phase, but very close when compared to PET-insulated pipe in the transportation phase. Typically, emissions from the extraction, processing of material feedstock, and fuel consumption used for manufacture and fossil fuels used in transportation are often responsible for the impacts on climate change. The impact on climate change is dominated by CO_2 emissions, which account for approximately 98% of all emissions to air in this LCA (**Section 4.3.2**). From a general viewpoint, this outcome is seen to be highly dependent on the manufacture of steel carrier pipe and energy consumption at the production facilities for electricity and heating and other operations. The insulation materials which still depend mainly on petroleum feedstocks also adds to the impacts seen in both extraction and manufacturing phases.

This corroborates with the LCA methodology report by the World Steel Association (2011), where it was found that about 8% of the total energy required to produce the steel - including raw material extraction and steel production processes is consumed indirectly during mining, preparation, and transportation of raw materials. The choice of energy sources is another reason for this result. At this point, it is necessary to reiterate that the LCI data used are average data across Europe. According to Eurostat (2021), electricity and heating in the European Union (EU) is from Petroleum products (crude oil (36 %), natural gas (22 %), renewable energy (15 %), nuclear energy, and solid fossil fuels (both 13 %). From an environmental standpoint, the effect of the over 50% share of fossils will be substantial.

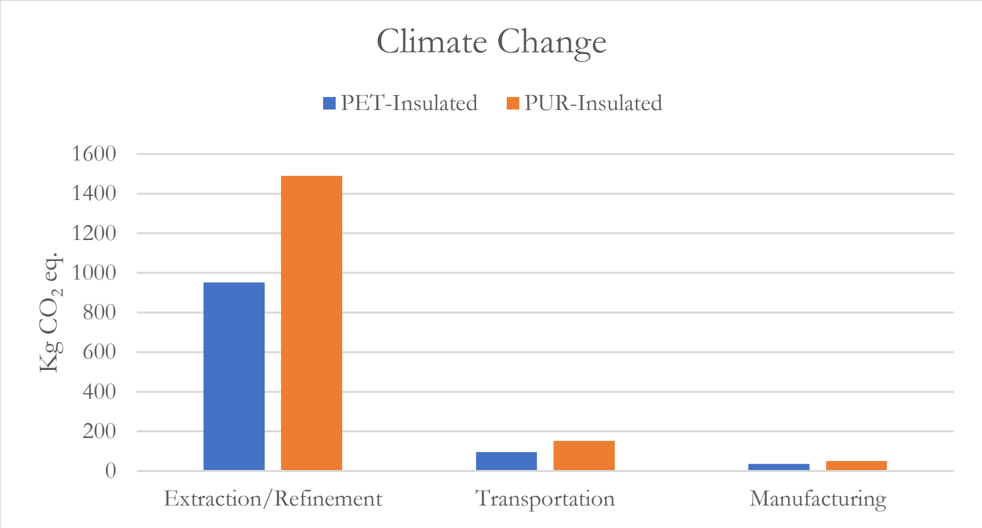

Figure 17. Contribution of the life cycle phases to Climate Change

4.3.2.2 Fossil depletion

Fossil depletion is linked to the usage of fossils fuels for energy. Actually, the factors responsible for this environmental impact are very much linked to that of the impact on climate change. Petroleum products are still used for heating and generating electricity in Europe (more than 36% according to Eurostat, 2021), except a few countries like Sweden, Norway, and Iceland that have a significant share of renewables in their energy mix. It is therefore inevitable for fossil depletion to be significant in these processes. According to Hopewell, et al., (2009), about 4% of the world's oil and gas production is used as a raw material for plastics production, and a further 3–4% is spent to provide energy for their production. This further explains the driving force for the significant impact seen in the extraction/refinement phase. Moreover, the core components of PUR foam are more energy and material intensive in comparison to PET foam. Hence the poor performance of the PUR foam insulated pipe.

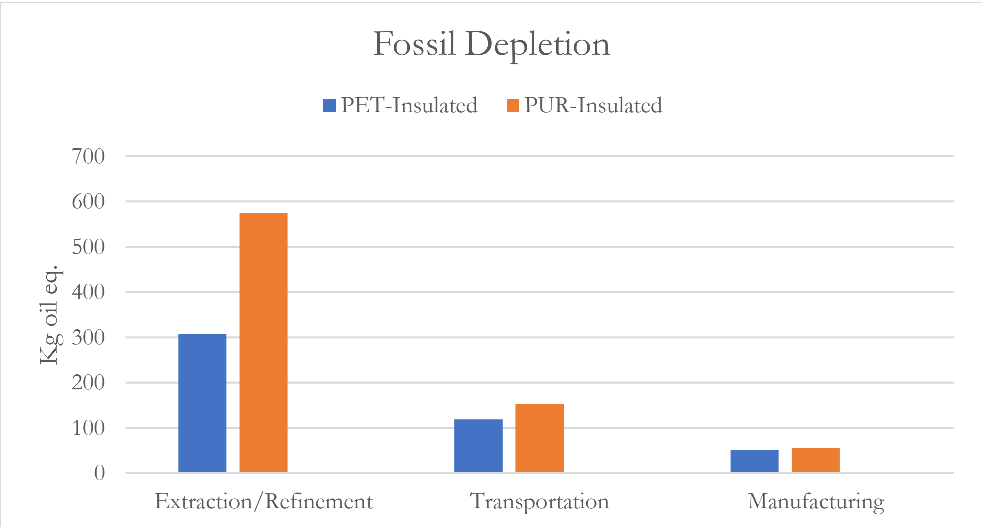

Figure 18. Contribution of the life cycle phases to Fossil Depletion

4.3.2.3 Freshwater Depletion

The freshwater depletion impact category contributes significantly to the overall environmental impact across all life cycle phases. As presented in **Figure 19**, it is evident that the impact is noticeable mainly in the extraction phase while the transportation and manufacturing phases are nearly unaffected. Furthermore, it can be seen that the combination of the raw materials used in the PUR foam insulated pipe accounts mainly for this outcome, particularly the steel for the carrier pipe and crude oil-based isocyanate in PUR foam. Virgin PET granulates also plays a part here. A typical area where water is used up includes water in chemical reactions, water absorbed into a component or waste stream, water lost to evaporation, and water discharged to a different water body than the one from which it was obtained. In the manufacturing phase, the link to water consumption is mainly in the production of power and fuels i.e., evaporative losses connected with the thermal generation of electricity from fossil and nuclear fuels, as well as evaporative losses owing to the hydropower dams.

Mielke, et al., (2010), explained that water is very important for resource extraction, but when compared to other industries like agriculture or municipal needs, water demands can have a significant impact on local water resources and increase conflicts between water users in areas where there is a lot of water stress. In oil and gas development, water is used in drilling and fracturing wells, refining, and producing electricity in some natural gas power plants (Allison & Mandler, 2018). Even though the amount and quality of water utilized, disposed of, or re-used vary greatly, it is still an obvious environmental concern (Mielke, et al., 2010).

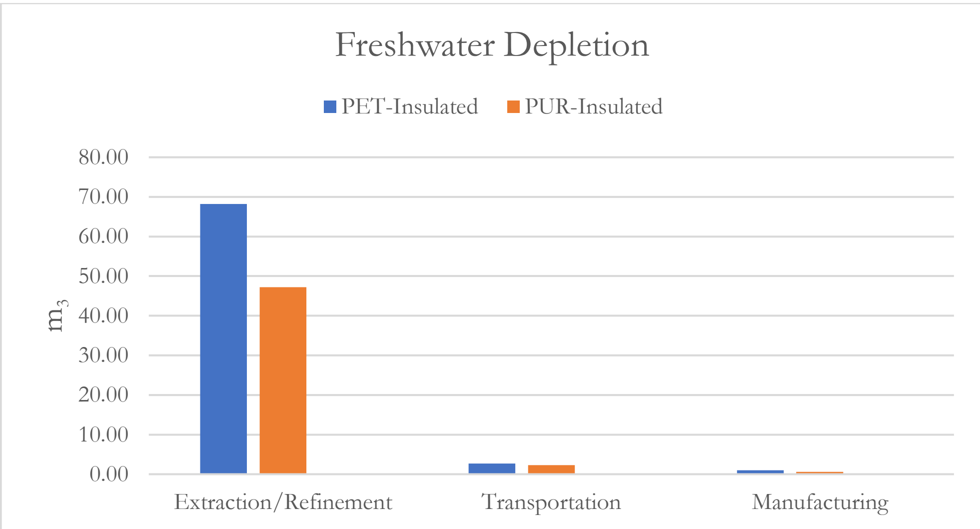

Figure 19. Contribution of the life cycle phases to Freshwater Depletion

4.3.2.4 Freshwater Eutrophication

The major contributors to eutrophication are nitrogen oxides (NOx) in the atmosphere, as well as nitrogen, phosphorus, ammonia, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) in water. As expected, the effect of extraction activities impacts freshwater eutrophication the most. PUR foam insulated pipe performs poorly as against the PET foam insulated pipe in this phase of the LCA while only traces were notices in the transportation and manufacturing phases. Steel pipe, diisocyanate and aluminium foil are the main contributing sources. The impact observed can be credited to the unplanned removal of vegetation cover from resource extraction sites, which can potentially increase the escape of nutrients from the soil into the surface and/or groundwater, thereby disrupting the naturally occurring nitrogen cycle. Also, according to the European Environment Agency (2001), the rapid increase in industrial production in recent times has resulted in large volumes of nutrient-rich wastewater, thereby promoting eutrophication.

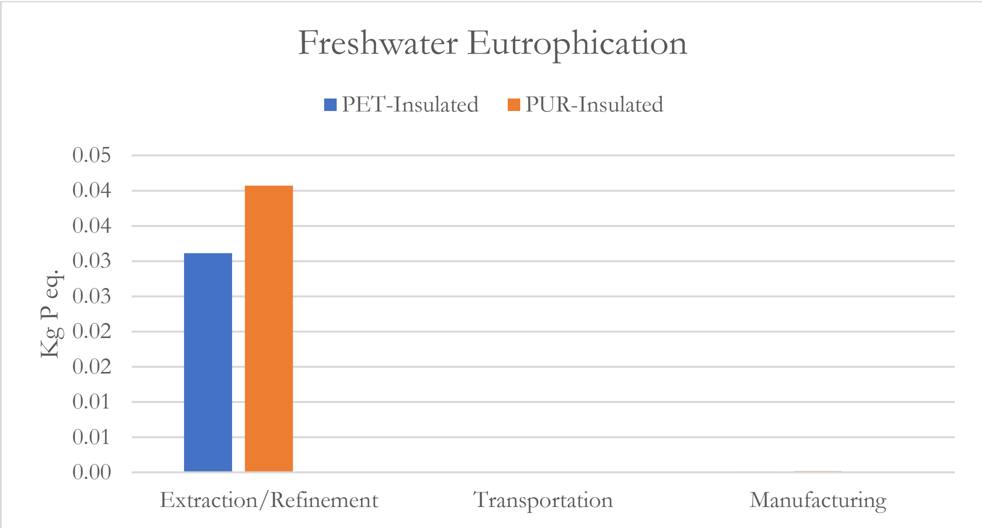

Figure 20. Contribution of the life cycle phases to Freshwater Eutrophication

4.3.2.5 Human Toxicity, Cancer

Human toxicity, cancer, considers the impact of the product system on human health through the emission of carcinogenic substances. The steel pipe in both pipes plays a significant part. The various processes used in the manufacture of steel pipes expose workers to physical factors such as heat, ionizing radiation, and noise while chemicals such as welding gases that contains manganese and other heavy metals may have a negative impact on the neurological, respiratory, and cardiovascular systems (Beuter, et al., 2004). In **Table 12**, it can be seen that The PUR foam insulated pipe is more toxic to human health. As previously stated in the introduction to this thesis, there are a few concerns about the safety of PUR foams especially in the manufacturing phase. Of the constituents used in the production of PUR foams, diisocyanate (commonly toluene diisocyanate -TDI and methylene diphenyl diisocyanate -MDI), are the contributions to the overall impact. According to Nuno et al., (2018), these compounds when not correctly handled may cause irritation of the mucous membranes of the eyes, the gastrointestinal tract, and the respiratory system. Direct skin contact might also result in a lot of swelling. Exposed persons are also at risk of severe asthma.

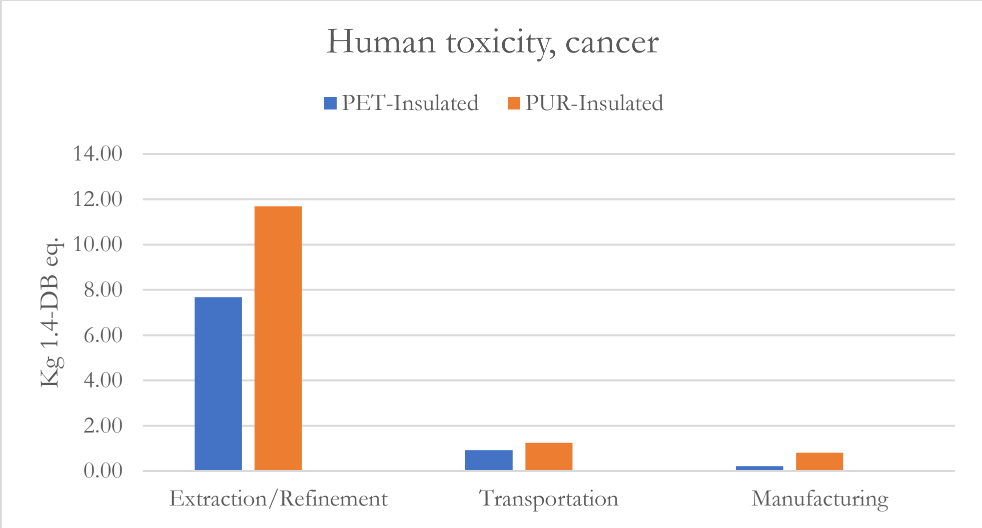

Figure 21. Contribution of the life cycle phases to Human toxicity, cancer

4.3.2.1.6 Land Use

The three indicators that make up the land use impact category are agricultural land occupation, urban land occupation, and natural land change. **Figure 22** shows an aggregation of these three land use categories as evaluate in the GaBi. Similar to previous impact categories, the impact of land use is mostly seen in the extraction and refinement phase. As usual, the steel carrier pipe is mainly responsible for this. Both PET and PUR foams also play a significant role here since the main raw material in their production emanates from crude oil extraction which is also a land-intensive process. Approximately 89% of the entire Land Use indicator value is attributed to the extraction of raw material. Raw materials are essentially mined out of the earth thereby putting pressure on land use, as such, this result is expected.

For example, in the case of the most important component in the product system by mass, steel, Sonter et al., (2014) explained that the global steel demand considerably drives land use within the confines of iron exploration and as a result, the direct effects of mining on native vegetation are excessively large. Moreover, there are also evidence that mining exploration development has slowed down the recovery of native forests, while land competition between mining corporations and urban developers exacerbated deforestation pressures.

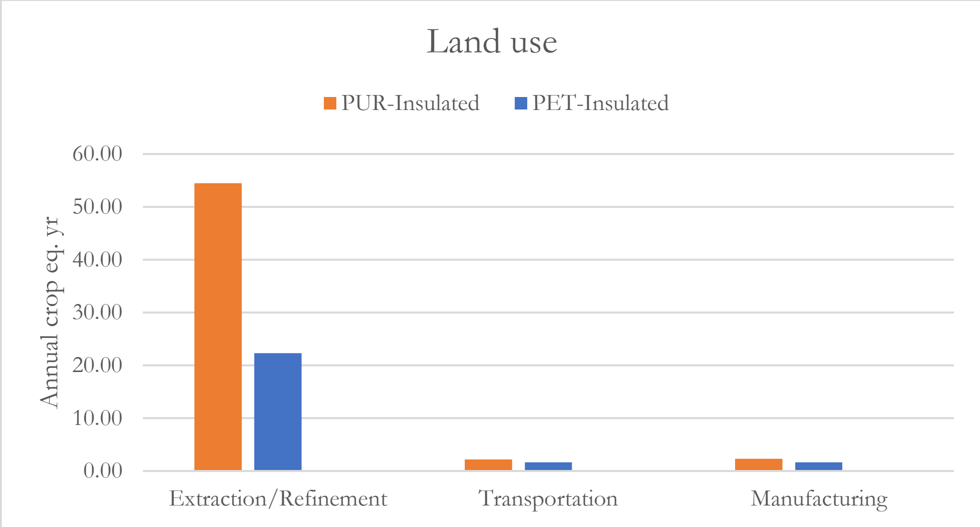

Figure 22. Contribution of the life cycle phases to Land Use

4.3.2.7 Marine Eutrophication

Here the results indicate that the impact on marine eutrophication is very minimal in caparison to the other impact categories, as it is only responsible for less than 2% overall. This is mainly because chemicals used in the refinement and extraction processes of major raw materials for both pipe types, which is the most impacted LCA phase, have very little or no nitrogen and phosphorus contents in them. As expected, the PUR foam insulated pipe is still the worst performer (see **Figure 23**) because nitrogen is commonly found in most amine catalyst and polyether polyols that are used in the PUR foam mixture. In some cases, to address the flammability of the blowing agent (cyclopentane), the phosphorus-based flame retardant is added to the mix that in turn potentially fuelling eutrophication down the line. Also, cleaning and releasing agents used during manufacture also play a small role.

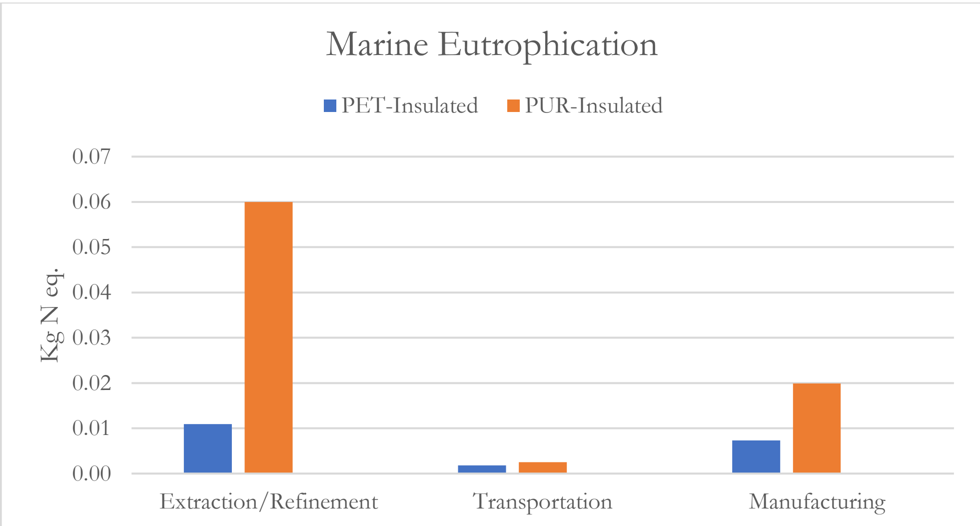

Figure 23. Contribution of the life cycle phases to Marine Eutrophication

4.3.2.8 Photochemical Ozone Formation, Ecosystem

Both PUR and PET foam insulated pipes impact photochemical ozone formation across all LCA phases but in varying degrees (see **Figure 24**). Apart from the steel pipe, which is obviously the most emitter, aluminium foil and HDPE granulates have the most influence in the photochemical ozone formation. This can be attributed to high hydrocarbon emissions into the atmosphere especially during the extraction of crude oil needed for production, but also to some extent the higher energy requirement during refinement. Long-haul transportation during sourcing of raw materials can potentially results in the emissions of noticeable volatile organic compounds (VOCs) in the transportation phase. Since the factors responsible here applies to both pipes, the notable reason for the poor performance of the PUR foam insulated pipe its higher SOx, NOx emissions.

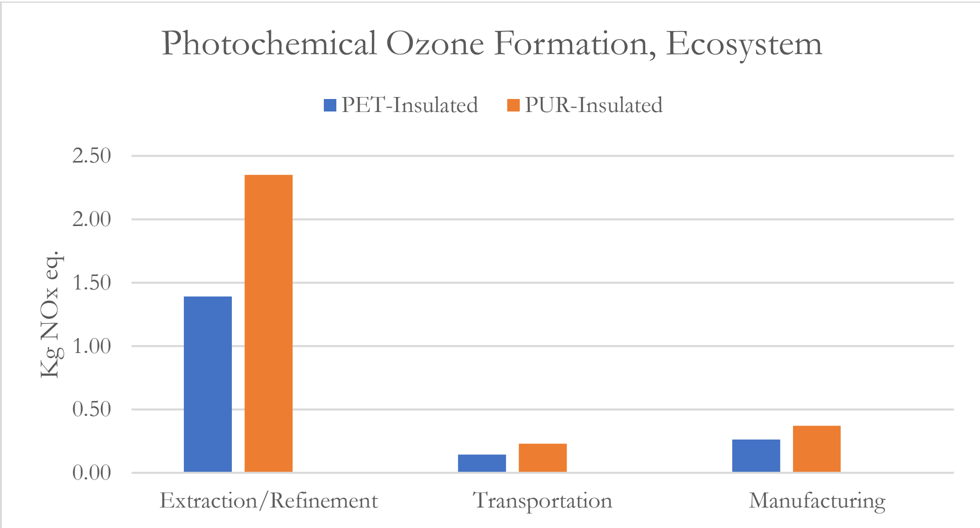

Figure 24. Contribution of the life cycle phases to Photochemical Ozone Formation, Ecosystem

4.3.2.9 Terrestrial Acidification

Emissions from the combustion of fossil fuel, particularly sulphur dioxide (SO_2) and nitrogen oxides (NOx), are often the most significant contributors to acidification. Acidification is exacerbated by emissions from the combustion of fossil fuels, particularly coal, to create grid energy (**Section 4.3.2)**. The results for the terrestrial acidification category are therefore very much similar to that of the climate change category across the LCA phases, except for the volume of emissions released which corresponds to the mass of the individual components of each pipe.

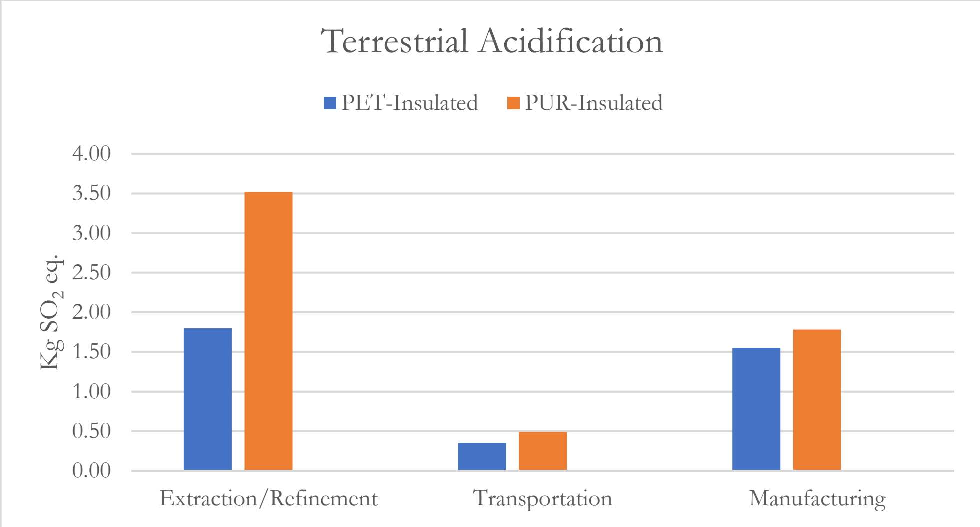

Figure 25. Contribution of the life cycle phases to Terrestrial Acidification

4.3.3 Environmental Impact of Insulations Materials

As previously stated, the effect of the pipe core materials utilized in the pipe production is mostly equivalent and the main difference between the pipes is essentially the type and quantity of the insulation. So, it was important to independently evaluate the impact of the production of insulations materials.

4.3.3.1 Comparison of PUR foam and Virgin PET foam

Although studies have suggested that PET foam have the potential to compete successfully against PUR foam (Mangs, 2005; Mangs et al., 2006; Jarfelt & Ramnäs (2008); Ivdre et al., 2020; Rossi et al., 2003), as such, it is important to evaluate these insulation materials more closely from the sustainability viewpoint. A sensitivity analysis of the studied system is also needed to determine to what extent an alternative insulation material like recycled PET will affect the overall outcome. **Tables 14** compares emissions of both materials while **Table 15** presents the comparison LCIA results.

Table 14. Emissions from insulations PUR foam and vPET foam (Kg)

Insulation	CO_2	NO_2	NO_X	SO_2
PUR Foam Mixture	35.02	0.004	0.0331	0.0216
PET Foam (Virgin)	14.88	0.00037	0.000795	0.00514

Table 15. Comparison of life cycle impact - PUR foam and vPET foam (Kg)

Impact category	Unit	PUR foam	vPET foam
Climate change	kg CO_2 eq.	355.32	119.13
Fossil depletion	kg oil eq.	148.8764	23.8435
Freshwater depletion	m3	10.56	18.63
Freshwater eutrophication	kg P eq.	0.00861	0.0060
Human toxicity, cancer	kg 1,4-DB eq.	4.2625	0.83
Land Use	Annual crop eq. yr	26.73	1.75

Marine eutrophication	kg N eq.	0.0114	0.0025
Photochemical ozone formation, ecosystem	kg NOx eq.	0.8555	0.27
Terrestrial acidification	kg SO_2 eq.	0.8295	0.357

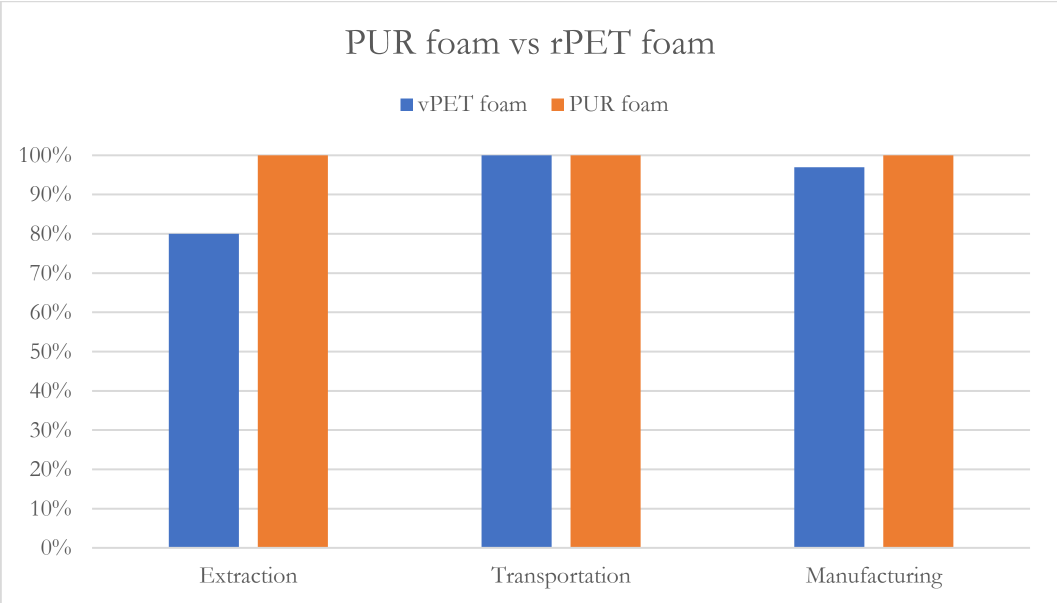

Figure 26. LCA phases in PUR foam vs recycled PET foam. *Within each impact category, the pipe with the highest environmental impact is presented as 100% impact, and the other as a percentage of that value.*

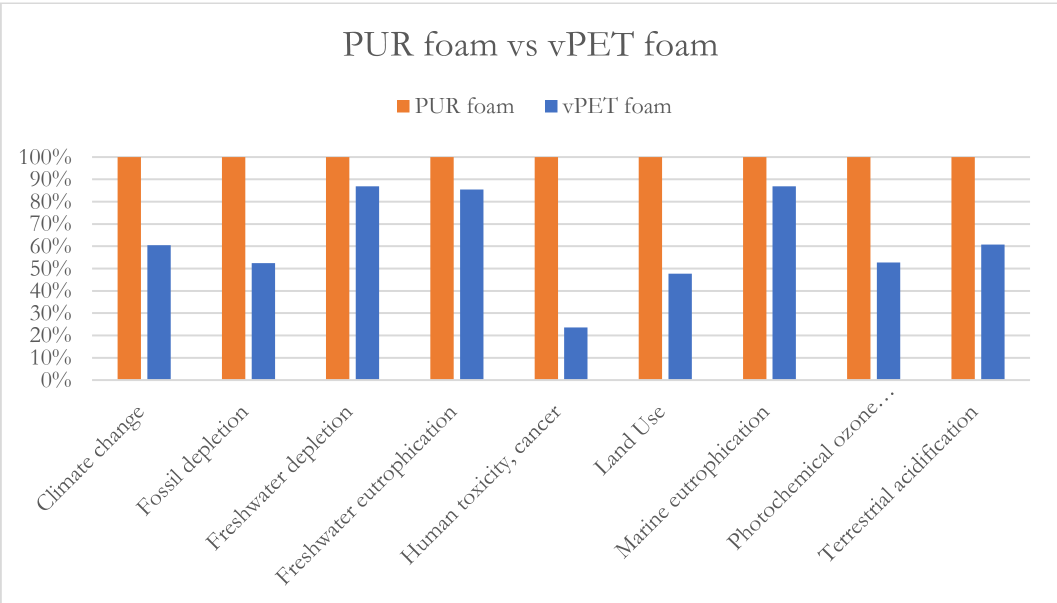

Figure 27. LCIA comparison of PUR foam and virgin PET foam. *Within each impact category, the pipe with the highest environmental impact is presented as 100% impact, and the other as a percentage of that value.*

Although both materials primarily originate from petrochemically produced raw materials, the vPET foam still has a less adverse impact on the environment (about 38% less on average). When the magnitude of the components is considered, PUR foam still performs poorly, despite that it is found to be 23% lower. The results have proven that a lower quantity of a particular material content does not always imply better environmental performance. With respect to the constituent materials involved, MDI contributes most of the impacts followed by polyols, but the impact of energy consumption is the highest (see **Appendix 2**).

Typically, MDI losses to air are extremely minimal partly due to its low volatility, as well as meticulous management of all phases of their lifetime, including manufacturing, transportation, usage, and disposal. They're made in closed systems with all vents controlled. As such, the only substantial losses occur when they are used in industrial operations, as in the case of PUR foam production (Tury, Pemberton & Bailey, 2003). These emissions vary significantly depending on the equipment utilized and improper mixing of chemicals. In addition, dust and shavings from the improperly mixed foam can release unreacted chemicals into the environment. These chemicals make their way into waterways and accumulate in aquatic life and organisms that feed on aquatic life (Berente, (2006).

4.3.3.2 Contribution Analysis of PUR foam

Haven identified that the PUR foam is the main cause of the potential environmental impacts posed by the studied system, an additional analysis of PUR foam was performed in order to determine the sources of high impacts of this specific process. **Figure 28** shows the process contributions of common components used in the production of PUR foam. The results show that polyol has high contributions to Climate change, Freshwater consumption, Freshwater eutrophication, and Photochemical ozone formation. Meanwhile, iisocyanate contributes the most to Fossil depletion, Human toxicity, Terrestrial acidification, and Land use, thereby accounting for 49% of overall impacts. The production of other chemical is contributes between 8% and 15% of the overall impact (See results in **Appendix 2F**).

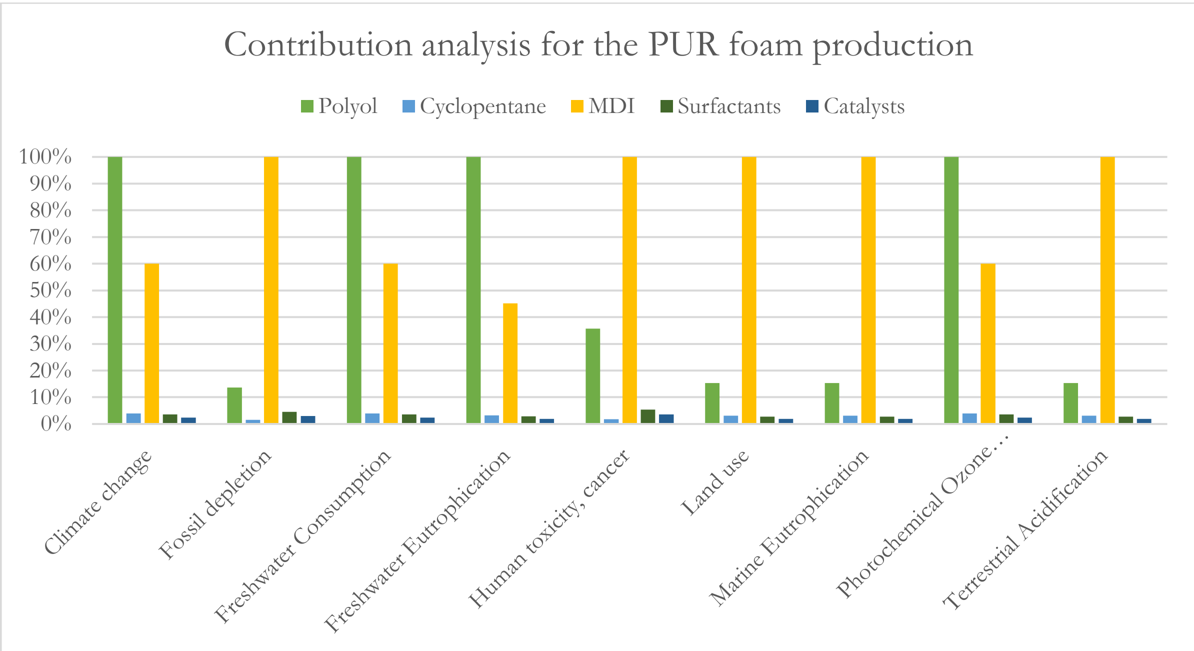

Figure 28. Contribution analysis of PUR foam production. *Within each impact category, the pipe with the highest environmental impact is presented as 100% impact, and the other as a percentage of that value.*

4.3.3.3 Comparison of Virgin PET foam and Recycled PET foam

Part of the objective of this work is to evaluate the product system from a circular economy perspective. In comparison with commonly used foam components, recycled PET presents itself as a good alternative to virgin PET in more ways than one. It is cost-effective and light, safer, and less poisonous. Recycling plastics saves energy and natural resources that would otherwise be used to make virgin plastics (Archna, 2015). This, therefore, makes it a suitable material for consideration.

In modelling this scenario, the recycled PET pellets as a raw material were taken to be sourced from a post-consumer plastic processing/shredding facility within the geographical location of the production plant in Denmark. **Tables 16** and **17** show a comparison of the emissions and environmental impact respectively.

Table 16. Emissions from insulations vPET foam vs rPET foam (Kg)

Insulation	**CO_2**	**NO_2**	**NO_X**	**SO_2**
PET Foam (Virgin)	4.88	0,0037	0,00795	0,00514
PET Foam (Recycled)	1.66	0,000289	0,00121	0,00452

Table 17. Comparison of life cycle impact - vPET foam vs rPET foam (Kg)

Impact category	**Unit**	**vPET foam**	**rPET foam**
Climate change	kg CO_2 eq.	119.13	2.86E+01
Fossil depletion	kg oil eq.	23.8435	1.12E+01
Freshwater depletion	m^3	18.63	2.55E+01
Freshwater eutrophication	kg P eq.	0.0060	3.24E-03
Human toxicity, cancer	kg 1,4-DB eq.	0.83	4.90E-01
Land Use	Annual crop eq. yr	1.75	8.40E-01
Marine eutrophication	kg N eq.	0.0025	1.88E-03
Photochemical ozone formation, ecosystem	kg NOx eq.	0.27	8.64E-02
Terrestrial acidification	kg SO_2 eq.	0.357	2.14E-01

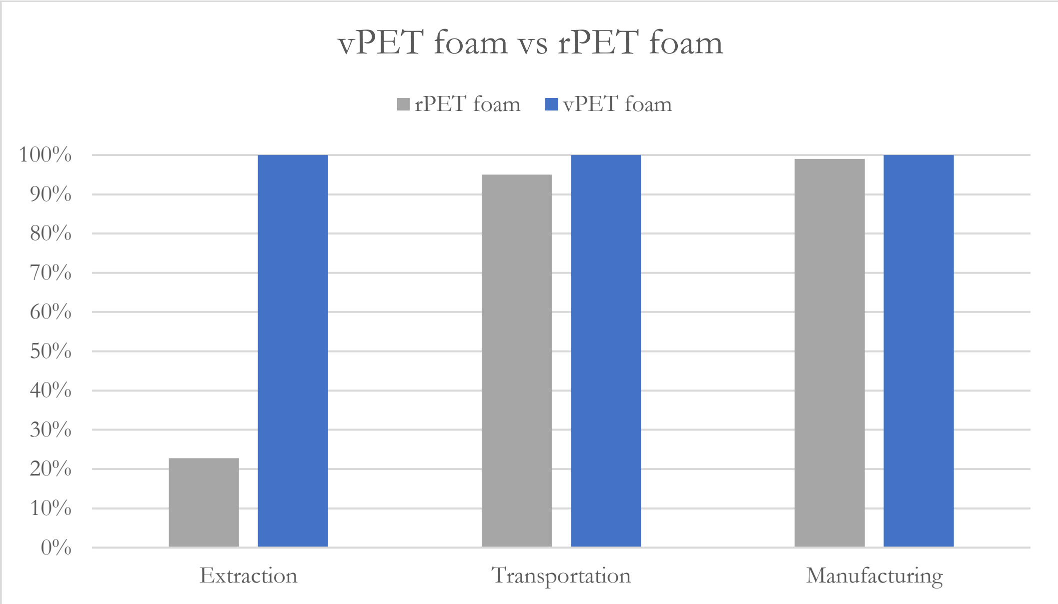

Figure 29. LCA phases in vPET foam vs rPET foam. *Within each impact category, the pipe with the highest environmental impact is presented as 100% impact, and the other as a percentage of that value.*

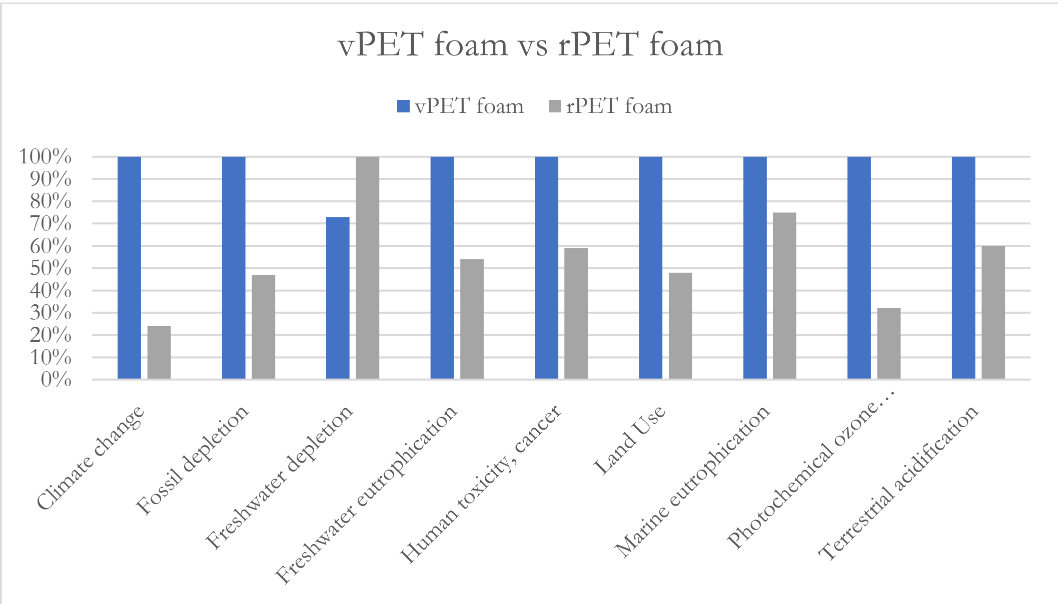

Figure 30. LCIA comparison of vPET foam vs rPET foam. *Within each impact category, the pipe with the highest environmental impact is presented as 100% impact, and the other as a percentage of that value.*

The results as seen in **Figure 30** demonstrated that the production of recycled PET foam has far less environmental impact due to its exceptional performance across most impact categories. The observed difference is very significant in that the utilisation of rPET foam reduced the overall impact by almost 48%. This outcome is significantly influenced by the highest savings is seen in the climate change in the extraction phases since the GHG emissions peculiar to the production of virgin materials have been avoided with the use of recycled materials. This is similar to the LCA study on Armacell PET foams, where it is reported that over 1.4 million PET bottles have been reused in the production process with a resultant savings of more than 63,000 metric tonnes in CO_2 emissions (Armacell, 2018). It is common knowledge that recycled PET reduces the need of virgin crude oil and natural gas, as well as the carbon dioxide emissions produced in the process. According to Benavides, et al., (2018), recycled PET offer both GHG emissions and fossil fuel consumption reductions ranging from 12% to 82% and 13% to 56% on a cradle-to-grave basis compared to fossil fuel-derived PET bottles. In terms of energy usage, recycled PET can significantly lower the energy required across the life cycle since the substantial energy inputs necessary to process the virgin materials greatly exceed the energy needs of the recycling process (Ncube & Borodin, 2013).

Surprisingly, even though the influence of rPET foam generates a much lower carbon footprint, it results in a much higher impact on freshwater depletion and marine eutrophication. The could be as a result of the water requirement which is necessary during the process of recycling (washing) post-consumer PET materials. In addition, the substances used as cleansing agenting during the washing generate effluents that are released into sewers and may end up in larger water bodies, thereby endangering marine life.

4.3.4 Virgin PET Foam Insulated Pipe vs Recycled PET Foam Insulated Pipe

The choice of insulation material is such an important subject with regards to the sustainability concerns in district heating since it is very vital in curtailing heat losses from a distribution system, therefore, it will be interesting to see how much influence the alternate insulation material will have on the overall environmental impact during the production of pre-insulated pipes.

It has been established that recycled PET foam is an excellent and more environmentally friendly insulation material based on how it outperforms the virgin PET and PUR foams, it is however important to examine how this material will influence the overall environmental impact of different aspects of the pipe production within the cradle to gate boundaries.

To evaluate the environmental implications of the nine impact categories, detailed research within the GaBi database was necessary to identify which material best suits the intended objective. "Post-Consumer Recycled PET" was identified and selected to replace originally used "Polyethylene terephthalate (PET, virgin)" in the model for PET foam production which is subsequently used in the pipe LCA model. All other parameters are left unchanged. **Table 18** presents the characterized results for recycled PET foam insulated pipe (rPET) compared to vPET foam insulated pipe. Also, **Figure 31** shows the differences between the reference scenarios and the modified ones as it affects the life cycle phases, and **Figure 32** describes how the comparison plays out across impact categories. Generally, the product with the higher environmental impact within each impact category and between pipe types is shown as 100% impact, and the other as a proportion of that value.

Table 18. Emissions from vPET foam pipe vs rPET foam pipe (Kg)

	CO_2	NO_2	NO_X	SO_2
vPET Foam Insulated Pipe	78.96	0.07	0.11	0.13
rPET Foam Insulated Pipe	61.88	0.031	0.053	0.107

Table 19: Characterized LCIA results of rPET foam pipe and vPET foam pipe

Impact Category	Unit	Extraction/Refinement		Transportation		Manufacturing	
		rPET-Insulated	vPET-Insulated	rPET-Insulated	vPET-Insulated	rPET-Insulated	vPET-Insulated
Climate change	kg CO_2 eq.	772.66	952	33.75	36	95.63	96
Fossil depletion	kg PM2.5 eq.	458.73	513	50.66	51.31	118.55	118.55
Freshwater Consumption	kg oil eq.	48.70	41.18	0.82	1	0.12	0
Freshwater Eutrophication	m^3	0.0303	0.03	0.0001	0.0001	0.00	0.0001
Human toxicity, cancer	kg P eq.	7.04	7.68	0.20	0.22	0.92	0.92
Land use	kg 1,4-DB eq.	21.20	22.30	1.65	1.67	1.65	1.65
Marine Eutrophication	Annual crop eq. yr	0.01	0.01	0.00	0.00	0.00	0.001
Photochemical Ozone Formation, Ecosystem	kg N eq.	1.25	1.39	0.26	0.26	0.14	0.14
Terrestrial Acidification	kg NOx eq.	1.77	1.80	0.11	0.11	0.19	0.19

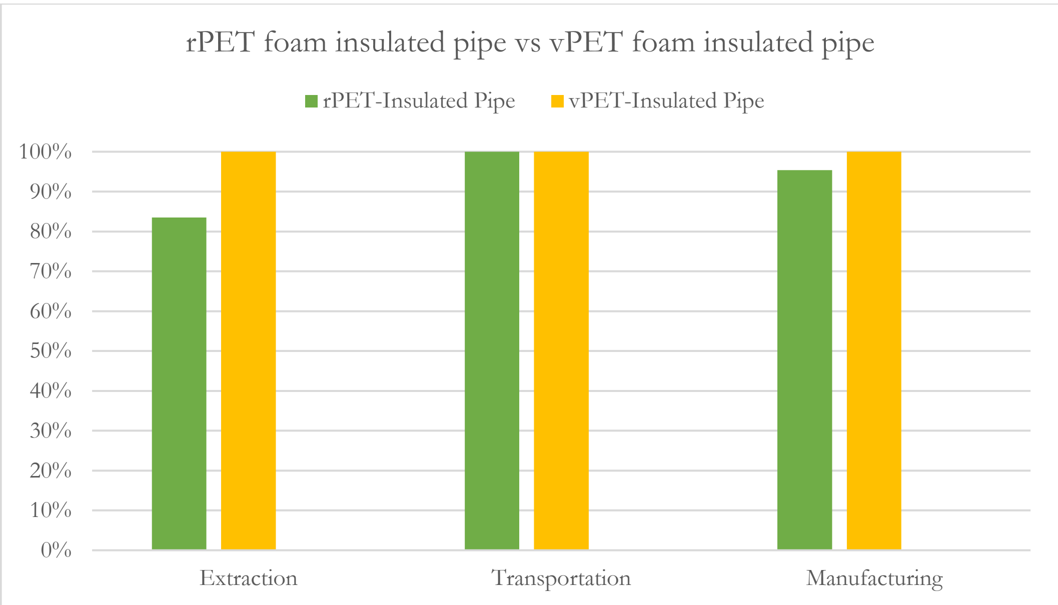

Figure 31. Life cycle phase comparison of rPET foam insulated pipe and vPUR pipe foam insulated pipe. *Within each impact category, the pipe with the highest environmental impact is presented as 100% impact, and the other as a percentage of that value.*

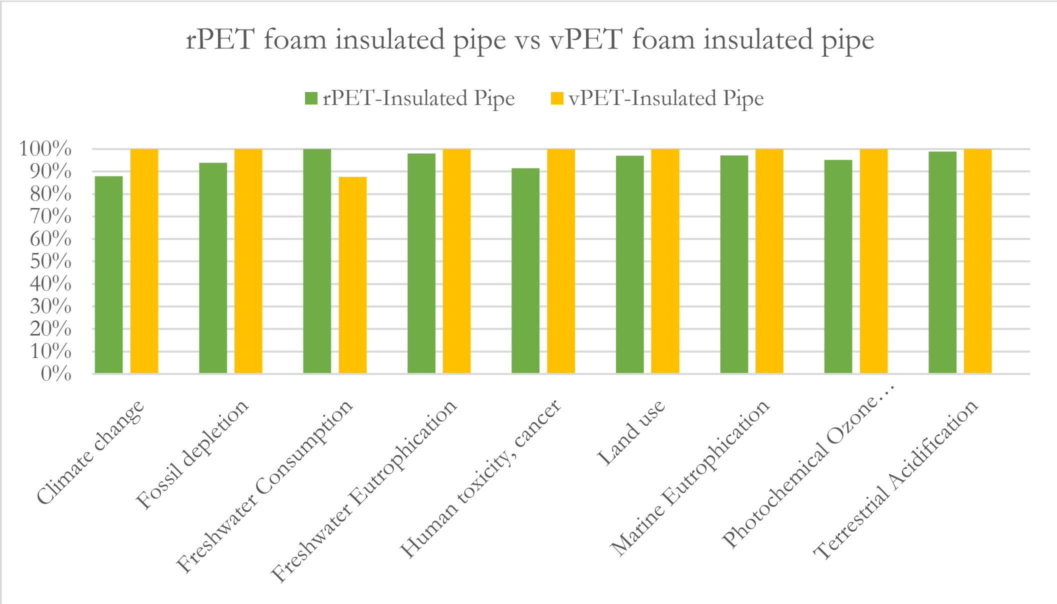

Figure 32. Impact categories of rPET foam insulated pipe and vPET pipe foam insulated pipe. *Within each impact category, the pipe with the highest environmental impact is presented as 100% impact, and the other as a percentage of that value.*

When vPET foam is replaced with rPET foam in the pipe product system, it was discovered that the environmental impact of the rPET foam insulated DH pipe was reduced by 11.69%. 67% of this reduction was noticed in the extraction and refinement phase and 32% in the manufacturing phase of the system boundary. As for the transportation, the change is very much negligible (less than 1%,). In general, there is a drop in the effect of this modified product system on the across almost all impact categories but for a few exceptions. The categories with the most significant reductions are climate change with 23.21%, followed by fossil depletion and photochemical ozone formation, at 12% and 10.3% respectively. The percentage reduction of the others ranges between 2 and 3%. Different studies have tried to determine how the use of recycled PET as a core feedstock in production processes has affected the environment. Hopewell, Dvorak, and Kosior (2009) claimed that, on average there is a net reduction of 1.5 tons of CO_2 equivalent per ton of rPET when combined with energy-saving requirements.

The majority of the emission gains are driven by the substitution of the production virgin PET which are energy intensive. An LCA by Burnley, Chilton & Nesaratnam (2010) revealed that recycled PET granules have significant environmental advantages over virgin PET fibers depending on the allocation mechanisms used, fuel energy savings of 40–85%, and global warming optional savings of 25–75% might be obtained. Burnley et al. (2010) also conducted a study on PET and found rPET to significantly cut CO_2, acid gases, particle matter, heavy metals, and dioxins. Chen, Pelton, & Smith (2016), compare the life cycle of fossil and bio-based PET and discovered that alternate paths to PET resin reduce GHG emissions by roughly 10% to 30% when compared to fossil fuel-derived PET resin.

Another interesting point is how the modified product system impacted freshwater consumption. Conversely, the effect on this impact category was worsened by a 15% increase in its contribution. This corroborates Jabłońska (2018), where it was affirmed that the growing recycling of post-consumer polyethylene terephthalate (PET) usually necessitates the use of extensive freshwater especially in the pre-washing process. The majority of plastic recycling factories currently use fresh water for this purpose, resulting in considerable volumes of effluent. Additionally, a study by Santos et al. (2005) on the washing of post-consumer PET materials found that 3 kg of pellets require roughly 80 dm^3 of water and the mechanical recycling of plastic wastes uses 3.48 kg of water for 1 kg of recycled PET. Furthermore, Benavides et al., (2018) water demand was found to be high during feedstock production and conversion in the case of biomass-derived PET, as well as during the recycling of bottles made from recycled PET.

In view of these results, it is still reasonable to conclude that using recycled PET as a starting material for production aids the reduction of environmental impacts. It is reasonable to conclude that rPET contributes to a more sustainable future that promotes environmental and social responsibility.

5.0 SUMMARY AND CONCLUSION

A complete environmental evaluation was undertaken utilizing ReCiPe's mid-point indicators to compare the life cycle assessments of polyurethane foam insulated pipe and polyethylene foam insulated pipe for the extraction, transportation, and manufacturing scenarios (cradle to gate). Key pipe components that impact these mid-point indicators are Steel pipes, virgin PET granulates PUR foams, Aluminium, and copper wire.

Detailed analysis of the product systems revealed that only the following nine out of seventeen ReCiPe mid-point indicators were significantly affected by the cradle-to-gate process chains: Climate change, Fossil depletion, Freshwater Consumption, Freshwater Eutrophication, Human toxicity, cancer, Land use, Marine Eutrophication, Photochemical Ozone Formation, Ecosystem, and Terrestrial Acidification. The most important environmental indicator is climate change and is mostly influenced by raw materials extraction and refinement. Accordingly, the results demonstrated that the extraction and refinement phase dominated the overall life cycle impacts, while the contribution of transportation to these impacts is the least. This is common in LCA studies since this phase (extraction/refinement) typically comprises a large number of product flows and activities, and the majority of raw material fabrications are rather widespread and are frequently connected with several industrial sectors.

The setup of the two product systems (PUR and PET foam insulated pipes) is very much identical but for the difference in the insulation materials and the varying quantity of all material apart from that of the steel pipe which is constant. When compared, the PUR foam insulated pipe emerges as the worse option in every impact category and accounts for 75% more impact in most of the environmental categories. Taking a step closer into how individual constituent materials performed through the LCA phases, steel pipe gives off the highest emission. This is somewhat anticipated for reasons like the amount of CO_2 emissions from steel manufacturing, which is almost double the amount of steel created (Hall, 2021), and steel production that could be responsible for up to 9% of direct emissions from global fossil fuel use (Worldsteel, 2020), etc. However, the main reason as it applies to this thesis, is that it accounts for approximately 78% and 60% of the total mass of the PUR foam insulated pipe and PET foam insulated pipe respectively. Consequently, the emissions are mostly noticeable in the climate change and fossil depletion impact categories. The quantitative amount of the steel pipe material influences the results in a more significant way and since material efficiency plays a crucial role in reducing environmental impacts, then, measures to reduce or even completely replace the use of steel have a greater potential to improve the environmental friendliness of the products system. Alternatively, new, and sustainable ways of sourcing steel pipe need to be worked out.

Furthermore, according to the findings, the transportation step has a minimal impact on the final result by contributing an approximately 11% to the total environmental effect across all considered categories. This solely depicts the shipment of raw material to the manufacturing plant and not the other movements of materials that occur within the facility. Another reason for the modest impact is the low emissions from diesel-fuelled heavy-duty trucks, which have decreased dramatically since the last two decades where the average sulphur level in diesel decreased from 400 parts per million to 3 parts per million, while nitrogen oxide emissions decreased from 9.04 grams per kilometre (EMEP/EEA, 2016).

When it comes to the manufacturing phase, which involves activities like extrusion, assembly, and processing, to a very large extent, the environmental impacts recorded here are mainly a result of the energy utilization in the production plant during these processes. Just like in other parameters the energy data category used in this LCA study is the European average. In the EU, renewable electricity generation has nearly doubled since 2005 to 34% of total electricity generation, and coal no longer supplies the majority of the EU's electricity. However, fossil fuels continue to generate the majority of electricity (38% of all generation in 2019). As such, the EU energy industry accounts for over a quarter of all EU greenhouse gas emissions, with combustion-based installations dominating the mix. It also contributes to acidification, eutrophication, and the creation of ground-level ozone (EEA, 2020).

Another point that stands out from the LCA results is how the insulation materials performed in comparison to one another. Since insulation is the main difference between both product systems, therefore, it is very important for the determination of savings in emissions brought to the systems. Looking at the trend in which the emissions and environmental impacts occur across different life cycle phases, it is very much identical to that of the overall production system with the acquisition of raw material extraction phase being the most relevant phase. The difference here is that in the manufacturing phase, the impact is slightly elevated relative to the entire system. i.e., where the manufacturing phase causes 21% of the impacts overall during the complete pipe manufacture, it is responsible for 38% of the impacts during the production of insulations. This means that asides from energy consumption, other activities like the mixing and preparation of chemicals necessary for the foam play a relevant role here. This is particularly the case in the production of PUR foam since the preparation of the mixture requires specialised procedure carried out within the production facility, which is potentially detrimental if not handled properly, thereby adding to the potential environmental impact at this phase in the LCA. In general, the production of virgin PET foam is more environmentally friendly by an average of 28%. Furthermore, contribution analysis showed that MDI is the main contributor while polyol only contributed to a smaller degree (0-9%) of the overall impacts of insulation.

When compared to the production process using recycled PET instead, the impact was further reduced by up to 60%. Recycled PET has the added benefit of being less energy-intensive than virgin PET (Armacell, 2016). The only cause for concern here is the observed negative impact on freshwater depletion of which the process of recycling PET is the culprit. As a mitigation to this potential issue, other methods of recycling PET which is less water-intensive like coagulation and flocculation combined to lower the number of pollutants and impurities in the post-washing wastewater to levels that allowed the water to be reused in the washing process (Jabłońska, 2018).

Further analysis was conducted to check how much influence a suitable substituent material, recycled PET, in place of virgin PET will have on the complete product system. It was shown that the production of PET foam with recycled PET as the main raw material is associated with further reduction in the impacts by approximately 12%. This savings is noticeable across almost all impact categories since the of the fossil-based PET has been avoided.

5.1 Uncertainties and Limitations

This LCA aims to compare the environmental impact of the manufacturing of two types of district heating pipes, but like any other environmental assessment tool, the LCA technique has its shortcomings. In this thesis, all site-specific information on processes was obtained from producers with the aid of a questionnaire specifically developed for this project. However, there is a chance that uncertainties will arise during data gathering, notably is the possibility of misrepresentation. To mitigate this, the questionnaire was double-checked by colleagues before being sent out. Regardless, data inaccuracies due to misinterpretations are likely unavoidable, so to address this, respondents were contacted for follow-up discussions in such circumstances where clarifications were required.

Since average European data was used during the modelling of different phases in the LCA, there is a high possibility that the outcome may not reflect the site-specific conditions of the system, since different locations have issues that are peculiar to them. The background database of GaBi Education 2.2 was utilized to calculate environmental impacts in the LCA modelling. There are restrictions in the database in terms of the countries in which operations can take place. As a result, when Europe 28 (EU28) is not available, Germany (DE) is chosen.

There was a need to estimate particular data collected in this study because the units of materials as provided were expressed in units other than what is required for correct input by the LCA software, consequently, there was a need to convert these to kg, m^3, and MJ as appropriate. When materials are made up of several components, it is also important to estimate the proportion of each component, such as the amount of insulation, jacket pipe, carrier pipe, and other components that make up the complete DH pipe. So, in this thesis, these were calculated based on information in product manuals, literature, and interviews, however, estimates may not be entirely perfect due to rounding errors and the like, but very close to the true values.

Another significant point as it relates to uncertainty has to do with the difficulties of working with free datasets and secondary data. On the other hand, it's uncertain how much more accurate a similar but pay-to-use dataset is. The key issue is determining how effectively the offered secondary data reflect and match the specific life cycle phases they are designed to represent.

5.2 Conclusion

It is clear that the recycled PET foam insulated pipe performs significantly better than the PUR foam insulated pipe from an environmental perspective. The findings demonstrated that it is possible to optimize the production of a district heating pipe by replacing the commonly used PUR foam with a more sustainable recycled PET foam thereby contributing to the larger vision of an environmentally friendly district heating system. This analysis shows that recycled PET foam has lower environmental impacts than corresponding virgin PET foam across the range of result categories analysed. Although reductions in life cycle impacts vary, the extraction phase is by far the largest life cycle contributor for all impacts studied. Development opportunities are however seen within energy consumption at the production facilities.

The idea of incorporating PET foam into the district heating ecology is unquestionably a worthwhile line of action on the correct track, with the majority of sustainability targets and measures emphasizing its environmental significance. Even as this technology advances, it makes sense to encourage the usage of recycled PET foam insulation as the potential for improvement in the long-term environmental performance very is high.

5.3 Further Research

The economical aspect is not included in this LCA. This is important because the financial implication of any project goes a long way in determining the viability of such a project. In this case, simply because the PET foam insulated pipe is more environmentally friendly does not necessarily mean it will be cheaper to produce. Hence, it may be interesting to evaluate other non-environmental variables not considered in this study that may prove to be a better criterion for choosing between one pipe and another – Life Cycle Costing.

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APPENDIX 1 - QUESTIONNAIRE

Suppliers were issued a data collecting form. The questionnaires submitted to suppliers are tailored to the specific production taking place at the site. All surveys cover general production statistics, material and chemical usage, water consumption, water treatment, energy usage, and transportation. To reflect the questions in the questionnaires, some general questions are presented below:

A. Background Information

i. Name of Organization
ii. Location of organization
iii. Designation of respondent

B. Technical Information

i. What are the intermediate raw materials used in the manufacturing process of pre-insulated pipes?
ii. Are materials sourced from a primary or secondary supplier?
iii. What is the sequence of operation in the manufacturing process? A flow diagram or Schedule of Program will be appreciated here.
iv. Are capital goods used in the manufacturing process?
v. What is the approximate annual production volume?
vi. Waste analysis - How much waste (%) is generated?
vii. How are generated waste typically handled? Reuse, recycle and/or incinerate?
viii. What is the annual electricity usage in the production area?
ix. What is the average annual production quota of the pipes that include aluminium barrier?

APPENDIX 2 - INVENTORY DATA

A. PUR-Insulated Pipe

Components		Mass	Unit
Aluminium foil [Metals]	Mass	0,38	kg
Copper wire [Metals]	Mass	0,57	kg
Electricity [Electric power]	Energy (net calorific value)	7,39	kwh
Lubricant (unspecified) [Operating materials]	Mass	1,43	kg
Polyethylene high density granulate (HDPE/PE-HD) [Plastics]	Mass	4,03	kg
Polyethylene low density granulate (LDPE/PE-LD) [Plastics]	Mass	1,21	kg
Polyethylene terephthalate granulate (PET, sc.) [Plastics]	Mass	0,31	kg
Polypropylene granulate (PP) [Plastics]	Mass	0,52	kg
Polyurethane mixture	Mass	3,86	kg
Silicone rubber (RTV-2, 25% siliceous sand) [Plastics]	Mass	0,20	kg
Steel billet (100Cr6) [Metals]	Mass	0,36	kg
Steel pipe [Metals]	Mass	23,86	kg

B. PET-Insulated Pipe

Components		Mass	Unit
Aluminium foil [Metals]	Mass	0,61	kg
Copper wire [Metals]	Mass	0,57	kg
Electricity [Electric power]	Energy (net calorific value)	9,63	kwh
Lubricant (unspecified) [Operating materials]	Mass	1,43	kg
PET foam [Material systems]	Mass	11,59	kg
Polyethylene high density granulate (HDPE/PE-HD) [Plastics]	Mass	4,30	kg
Polyethylene low density granulate (LDPE/PE-LD) [Plastics]	Mass	1,21	kg
Polyethylene terephthalate granulate (PET, sc.) [Plastics]	Mass	0,31	kg
Polypropylene granulate (PP) [Plastics]	Mass	0,52	kg
Silicone rubber (RTV-2, 25% siliceous sand) [Plastics]	Mass	0,20	kg
Steel billet (100Cr6) [Metals]	Mass	0.36	kg
Steel pipe [Metals]	Mass	23,86	kg

C. PUR-foam Input data

Components		Weight	Unit
Polyol	Mass	1.87	kg
Cyclopentane	Mass	0.04	kg
MDI	Mass	1.87	kg
Electricity [Electric power]	Energy (net calorific value)	9.3	kwh
Other additives	Mass	0.08	kg

D. PUR foam emissions as per material contribution (Kg)

Components	CO_2	NO_2	NO_X	SO_2
Polyol	6.30	7.20E-04	5.96E-03	3.89E-03
Cyclopentane	1.45	1.66E-04	1.37E-03	8.95E-04
MDI	9.105	1.04E-03	8.61E-03	5.62E-03
Electricity [Electric power]	15.209	1.74E-03	1.44E-02	9.38E-03
Stabilizing agent [Operating materials]				
Catalyst	3.15	3.60E-04	2.98E-03	1.94E-03

E. PET-foam (Virgin and Post Consumer) Input data

Components		Mass	Unit
Carbon dioxide [Inorganic intermediate products]	Mass	0,001	kg
Electricity [Electric power]	Energy (net calorific value)	35.77	kwh
Epoxy resin [Plastics]	Mass	0,29	kg
Stabilizing agent [Operating materials]	Mass	0,06	kg
Surfactants (tensides) [Operating materials]	Mass	0,23	kg
Polyethylene terephthalate (PET, unspecified)	Mass	11,01	kg

F. PUR foam emissions as per material contribution (kg)

Components	CO_2	NO_2	NO_X	SO_2
Carbon dioxide [Inorganic intermediate products]	1.49E-01	3.70E-06	7.95E-06	5.14E-05
Electricity [Electric power]	7.14E+00	1.78E-04	3.82E-04	2.47E-03
Epoxy resin [Plastics]	2.98E+00	7.40E-05	1.59E-04	1.03E-03
Stabilizing agent [Operating materials]	1.93E+00	4.81E-05	1.03E-04	6.68E-04
Surfactants (tensides) [Operating materials]	1.49E+00	3.70E-05	7.95E-05	5.14E-04

G. Contribution analysis of PUR foam insulated pipe production

	Climate change	**Fossil depletion**	**Freshwater Consumption**	**Freshwater Eutrophication**	**Human toxicity, cancer**	**Land use**	**Marine Eutrophication**	**Photochemical Ozone Formation, Ecosystem**	**Terrestrial Acidification**
	kg CO^2 eq.	kg PM2.5 eq.	kg oil eq.	m^3	kg P eq.	kg 1,4-DB eq.	Annual crop eq. yr	kg N eq.	kg NOx eq.
Copper wire [Metals]	33.84	5.52	1.53E-01	3.23E-04	2.48E-03	1.65E-01	4.00E-04	5.90E-02	3.95E-02
Steel billet [Metals]	16.92	3.94	1.97E-01	8.15E-05	1.25E-01	1.27E-02	2.10E-04	2.95E-02	7.90E-02
Steel welded pipe (carrier pipe)	727.56	297.75	2.12E+01	1.31E-02	2.91E+00	1.68E+01	1.00E-02	8.85E-01	1.66E+00
Aluminium foil [Metals]	50.76	15.67	2.40E+00	1.64E-03	4.13E-01	2.95E+00	1.80E-03	8.85E-02	2.77E-01
Electricity [Electric power]	253.80	101.86	8.64E+00	8.61E-03	6.88E-01	5.90E+00	9.60E-03	2.95E-01	5.53E-01
Lubricant [Operating materials]	23.84	3.04	4.42E-01	8.20E-04	1.20E-01	1.18E+00	5.53E-04	5.90E-02	3.95E-02
Polyethylene low density granulate (LDPE/PE-LD) [Plastics]	16.65	6.56	4.76E-01	2.24E-04	1.26E-01	5.90E-01	1.20E-03	2.37E-02	1.19E-01
Polyethylene high density granulate (HDPE/PE-HD) [Plastics]	84.60	47.01	4.32E+00	3.69E-03	6.88E-01	3.32E+00	3.00E-03	2.07E-01	2.37E-01
Polyethylene terephthalate granulate (PET, sc.) [Plastics]	5.69	2.22	1.74E-01	2.87E-04	2.54E-02	1.93E-01	3.00E-04	3.60E-02	4.20E-02
Polypropylene granulate	15.47	2.30	2.53E-01	1.17E-04	1.38E-01	1.18E+00	6.00E-04	5.90E-02	2.72E-02
PUR foam Mixture	355.32	148.88	1.06E+01	8.61E-03	4.26E+00	2.67E+01	1.14E-02	8.56E-01	8.30E-01
Silicone rubber [Plastics]	1.41	0.27	9.31E-02	1.51E-05	8.28E-02	3.30E-02	6.18E-05	1.08E-01	1.06E-02
Solid Polyurethane (PU) in waste incineration plant	52.76	0.44	6.47E-02	1.98E-05	1.29E-01	7.61E-02	3.71E-04	1.77E-01	1.99E-02

H. Contribution analysis of vPET foam insulated pipe production

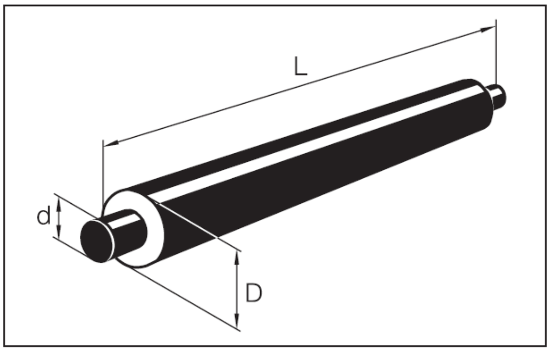
	Climate change	**Fossil depletion**	**Freshwater Consumption**	**Freshwater Eutrophication**	**Human toxicity, cancer**	**Land use**	**Marine Eutrophication**	**Photochemical Ozone Formation, Ecosystem**	**Terrestrial Acidification**
	kg CO^2 eq.	kg PM2.5 eq.	kg oil eq.	m^3	kg P eq.	kg 1,4-DB eq.	Annual crop eq. yr	kg N eq.	kg NOx eq.
Copper mix (Copper wire)	33.84	5.52	1.53E-01	3.23E-04	2.48E-03	1.65E-01	4.00E-04	5.90E-02	3.95E-02
Steel billet (Steel Clips)	16.92	3.94	1.97E-01	8.15E-05	1.25E-01	1.27E-02	2.10E-04	2.95E-02	7.90E-02
Steel welded pipe (carrier pipe)	727.56	297.75	2.12E+01	1.31E-02	2.91E+00	1.68E+01	1.00E-02	8.85E-01	1.66E+00
Aluminium foil	54.15	19.07	1.38E+00	1.25E-03	3.53E-01	1.54E+00	4.00E-04	5.40E-02	2.31E-01
Electricity grid mix	253.80	101.86	8.64E+00	8.61E-03	6.88E-01	5.90E+00	9.60E-03	2.95E-01	5.53E-01
Lubricants at refinery ts	23.84	3.04	4.42E-01	8.20E-04	1.20E-01	1.18E+00	5.53E-04	5.90E-02	3.95E-02
Polyethylene Linear Low Density Granulate (LLDPE/PE-LLD) (Packaging/Labelling)	16.65	6.56	4.76E-01	2.24E-04	1.26E-01	5.90E-01	1.20E-03	2.37E-02	1.19E-01
Polyethylene pipe (PE-HD) (Jacket pipe)	151.62	76.30	6.21E+00	3.44E-03	6.17E-01	4.32E+00	5.00E-04	1.26E-01	1.26E-01
Polyethylene terephthalate granulate (End cap)	5.69	2.22	1.74E-01	2.87E-04	2.54E-02	1.93E-01	3.00E-04	3.60E-02	4.20E-02
Polypropylene granulate (Spacers)	119.13	23.84	1.86E+01	6.02E-03	8.35E-01	1.75E+00	2.50E-03	2.70E-01	3.57E-01
PUR foam Mixture (Insulation)	1.41	0.27	9.31E-02	1.51E-05	8.28E-02	3.30E-02	6.18E-05	1.08E-01	1.06E-02

I. Environmental impact of PUR foam production (Contribution analysis) (Kg)

Impact Category	Polyol	Cyclopentane	MDI	Electricity [Electric power]	Surfactants	Catalysts
Climate change	177.66	7.1064	106.596	53.298	6.39576	4.26384
Fossil depletion	13.398876	1.488764	98.258424	28.286516	4.466292	2.977528
Freshwater Consumption	5.28	0.2112	3.168	1.584	0.19008	0.12672
Freshwater Eutrophication	0.0053382	0.0001722	0.0024108	0.0007749	0.000155	0.0001033
Human toxicity, cancer	0.8525	0.042625	2.387	0.76725	0.127875	0.08525
Land use	2.673	0.5346	17.3745	4.0095	0.48114	0.32076
Marine Eutrophication	0.00114	0.000228	0.00741	0.00171	0.0002052	0.0001368
Photochemical Ozone Formation, Ecosystem	0.42775	0.01711	0.25665	0.128325	0.015399	0.010266
Terrestrial Acidification	0.08295	0.01659	0.539175	0.124425	0.014931	0.009954

APPENDIX 3 - CALCULATIONS OF PIPE COMPONENTS

With reference to the Logstor Product Catalog, (2020) Product Catalog, (2020) was selected.



A. PUR-Insulated Pipe Components

i. Mass of Steel carrier pipe per metre length (Carrier pipe):

Steel pipe diameter = 110,7mm (DN100)
Steel pipe wall thickness = 3.6mm

Mass = Density x Volume
Steel density = 7850 kg/m^3

But Volume (V) = Circumference x Pipe length x Pipe wall thickness
V = (π x 0.1107m) x 1m x 0.0036m
V = 0.00125 m^3
Therefore,
Mass = 7850 kg/m^3 x 0.00125 m^3
Mass = 9,82kg/m x 2.43m (as per functional unit)
Total steel pipe Mass = 23.86kg

ii. Mass of PUR foam per metre length (Insulation):

PUR foam diameter = Pipe diameter (D) – Jacket pipe thickness
= 200mm – 4mm – 40.85mm
= 155,15mm
PUR foam thickness = 196mm – 114.3mm
= 81.7 / 2 = 40,85mm

Mass = Density x Volume
PUR foam density = 80 kg/m3

But Volume (V) = Circumference x Pipe length x Pipe wall thickness
V = (π x 0.15515) x 1m x 0.04085m = 0.0199m^3

Therefore,

$$\text{Mass} = 80\ kg/m^3 \times 0.0199\ m^3$$
$$= 1.592kg/m \times 2.43m \text{ (as per functional unit)}$$

PUR foam Mass = 3.86kg

iii. Mass of HDPE per metre length (Jacket pipe):

HDPE diameter = 200mm – 4mm (thickness) = 196mm

HDPE Mass = Density x Volume
HDPE density = 940 kg/m^3

But Volume (V) = Circumference x Pipe length x Pipe wall thickness

$$V = (\pi \times 0.196) \times 1m \times 0.002m$$
$$V = 0.00123m^3$$

Therefore,

$$\text{Mass} = 940\ kg/m^3 \times 0.00123\ m^3$$
$$= 1{,}156kg/m \times 2.43m \text{ (as per functional unit)}$$

HDPE Mass = 2.81kg

B. PET foam insulated pipe components

i. PET foam thickness

To determine the insulation thickness that fulfils the requirements of the functional unit, the formula for the rate of heat transfer is used to solve for insulation thickness with the following parameters:

Pipe length = 6m
Steel pipe diameter = 114.3mm (DN100)
Steel pipe thickness = 3.6mm
Jacket pipe diameter = 200mm
HDPE thickness = 2mm
Thermal conductivity of PUR foam = 0.027W / mK
Maximum continuous operating temperature = 90oC

Using the formula: $Q = 2\pi kN\ (Tp-Ti) / \ln\ (Ri/Rp)$,
Where:
K = 0.027
N = 6m
Tp = 90°C
Ti = 22°C
Ri = 98mm
Rp = 53.55mm

Q value was calculated to be 114.61 W / m

Since Q is constant for pipe types (necessary to ensure heat loss is same for pipes) and the thermal conductivity of PET foam is 0.032W / mK, applying the same formula, the equivalent thickness of PET foam is calculated to be:

$114.61 = 2 \pi \times 0.032 \times 6 \text{ x } (90 - 22) \div \ln (Ri / 0.05355)$
$\ln (Ri / 0.05355) = 2 \pi \times 0.032 \times 6 \text{ x } (90 - 22) / 114.61 = 0.716$

Hence, $Ri = 0.05355 \times e0.716$
$Ri = 0.05355 \times 2.718 = 0.146$ m

Hence, insulation thickness = Ri - Rp = 0.146 - 0.05355 = 0.09201m
Insulation thickness (PET foam) = 92.01 mm

ii. Mass of PET foam per metre length (Insulation):

Pipe diameter = 302,32mm
PET foam diameter = Pipe diameter (D) – Jacket pipe thickness – ½ insulation thickness (midpoint)
= 302,32mm – 4mm – 92.01mm
= 206,31mm

Mass = Density x Volume
PUR foam density = 80 kg/m3

But Volume (V) = Circumference x Pipe length x Pipe wall thickness
$V = (\pi \text{ x } 0.20631) \text{ x } 1\text{m x } 0.09201\text{m}$
$V = 0{,}0596\text{m}^3$
Therefore,
$\text{Mass} = 80 \text{ kg/m}^3 \text{ x } 0{,}0596 \text{ m}^3$
= 4.77kg/m x 2.43m (as per functional unit)
PET foam Mass = 11.59kg/m

iii. Mass of HDPE per metre length (Jacket pipe):

HDPE diameter = 302,32mm – 4mm (thickness) = 300.32mm

HDPE Mass = Density x Volume
HDPE density = 940 kg/m^3

But Volume (V) = Circumference x Pipe length x Pipe wall thickness
$V = (\pi \text{ x } 0.30032) \text{ x } 1\text{m x } 0.002\text{m}$
$V = 0.0019\text{m}^3$

Therefore,

$$\text{Mass} = 940 \text{ kg/m}^3 \text{ x } 0.0019 \text{ m}^3$$
$$= 1{,}77\text{kg/m x } 2.43\text{m (as per functional unit)}$$

HDPE Mass = 4.30kg/m

iv. **Mass of Steel carrier pipe per metre length (Carrier pipe):**
Mass of Steel carrier pipe = 237.6kg (Refer to calculation for PUR-insulated pipe (1a))

<u>C. Surveillance – Copper Wire</u>

Wire thickness = 3mm
Total length = 3m (as per functional unit 2.42m + extra on both ends)
Copper density = 8940 kg/m^3

Mass = Density x Volume
Volume = surface area x length

$$= \pi \text{ x } 0.0015^2\text{m x } 3\text{m} = 0.000021 \text{ m}^2$$

Therefore,

Mass = 8940 kg/m^3 x 0.000021 m^2
Mass = 0.19kg
Since 3x surveillance wire are usually used, then
Copper Wire Mass = 0.57kg

<u>D. Diffusion Barrier – Aluminium Foil</u>

i. **PUR-insulated Pipe**

Volume of aluminium foil = Circumference x Pipe length x Foil thickness

$$= (\pi \text{ x } 0.29832.\text{m}) \text{ x } 2.43\text{m x } 0.00005\text{m}$$
$$= 0{,}000047 \text{ m}^3$$

Mass = Density x Volume
Aluminium foil density = 2710kg/m^3

Therefore,

Mass = 2710 kg/m^3 x 0,000047m^3 = 0.13kg
But 3x layers of barrier is typically used (according to pipe manufacturer)
Aluminium Foil = 0.38kg

ii. PET-insulated Pipe

Volume of aluminium foil = Circumference x Pipe length x Foil thickness

= (π x 0.196m) x 2.43m x 0.00005m

= 0.000075 m^3

Mass = Density x Volume

Aluminium foil density = 2710kg/m^3

Therefore,

Mass = 2710 kg/m^3 x 0,000075 m^3 = 0.20kg

But 3x layers of barrier is typically used (according to pipe manufacturer)

Aluminium Foil = 0.61kg

E. Percentage Waste at Plant

The quantities of waste generated at planted is presented as average values of data as collected through the questionnaire.

Components	%
Steel Pipe	2,91
PUR foam	2,13
HDPE – PUR-insulated pipe	0,69
PET foam	0,25
HDPE – PET-insulated pipe	0,44

Source: Questionnaire