SELECTING MATERIALS FOR POTABLE WATER PIPES FROM AN ENVIRONMENTAL PERSPECTIVE
– life cycle assessments of four chosen pipe materials

MILJØRIKTIG MATERIALVALG I DRIKKEVANNSNETTET
– livsløpsanalyser av fire utvalgte rørmaterialer

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PREFACE

This thesis is written as a part of the Master study Water and environmental technology at the Department of Mathematical Sciences and Technology, Norwegian University of Life Sciences.

Sweco Norway has initiated the project, and assisted with two academic supervisors. The topic of the thesis is life-cycle assessment of pipe materials with respect to sustainability and the environment. The multidisciplinary topic has given me useful insight into both the LCA methodology and the technical aspects of the selected pipe materials.

I would like to thank my supervisor at the University, Jarle Tommy Bjerkholt, for valuable counseling. Thanks to Ola Moa Gausen, LCA expert in Sweco, for many useful suggestions and help with the software. And a big thank you to my supervisor Øystein Rapp (Sweco) who has assisted me with good advice and technical support over the period I have written this thesis.

I have been totally dependent on cooperation with the pipe manufacturers and pipe suppliers, and I want to thank everyone I have been in contact with while gathering input data. I am grateful for the benevolence you have met me with.

I would also like to thank all of my peer students , and of course Andreas.

This is a translated version of the thesis, prepared in 2015.

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ABSTRACT

In Norway, four main types of pipe material are currently being used in the installation of new potable water pipeline networks: ductile iron, fibreglass reinforced polyester (GRP), polyethylene (PE) and polyvinyl chloride (PVC). In this study, these pipe materials are compared from a life cycle perspective.

The purpose of a life cycle assessment is to consider the scope and distribution of environmental loads associated with a product or service, in this case potable water pipes. Studies have not previously produced consistent results as regards which pipe materials are superior or inferior with respect to any others. However, a number of studies have concluded that the majority of the environmental impacts originate from processes associated with the extraction and processing of raw materials used in the manufacture of pipes.

The life cycle analyses were performed using the SimaPro software. The life cycles are divided into the following phases: raw materials, energy and transportation. The results show how different environmental stresses are distributed between these phases. It is apparent that the 'raw materials' life cycle phase dominates the impact of plastic-based pipe materials, while the contribution of environmental load associated with ductile iron is fairly evenly distributed between all life cycle phases.

The environmental indicator 'climate change' (also known as 'global warming potential' or GWP) is often used as an appropriate environmental parameter, and in this study PVC accounts for the greatest proportion of CO_2 equivalents, whereas the proportion from GRP is the lowest, about a quarter of that of PVC.

Two different methods are used in SimaPro to determine the overall load from the environmental impact categories 'human health', 'ecosystem' and 'resources' associated with each of the pipe materials. Both methods indicate that PE and PVC are the biggest contributors, while GRP contributes the least.

Sensitivity analysis show that the type of electricity mix used may be crucial for the analysis results, while changes in the transportation phase must be substantial in order to be decisive. The picture is different if the pipe diameter is increased, because the wall thickness and weight of plastic pipes increase to a greater extent than the other pipe materials. The greatest uncertainty in the study relates to the analysis input data, which varies depending on the sources used, and complicates the basis for comparison. However, most of the results would need a substantial margin of error in order to change.

SAMMENDRAG

I Norge i dag er det hovedsakelig fire rørmaterialer som benyttes ved nylegging av vannledningsnett: duktilt støpejern, glassfiberarmert polyester (GRP), polyetylen (PE) og polyvinylklorid (PVC). I denne komparative studien er disse fire rørmaterialene vurdert ved hjelp av livsløpsbetraktninger.

Hensikten med en livsløpsanalyse er å vurdere omfanget og fordelingen av de totale miljøpåvirkninger assosiert med et produkt eller tjeneste, i dette tilfellet drikkevannsrør. Tidligere relevante studier har ikke gitt samsvarende resultater med hensyn på hvilke rørmaterialer som kommer godt eller dårlig ut, men flere konkluderer med at hovedvekten av miljøpåvirkninger kommer fra prosesser tilknyttet utvinning og foredling av råstoffene som benyttes i produksjonen av rør.

Livsløpsvurderingene i denne studien er utført med dataverktøyet SimaPro. Livsløpene er delt inn i fasene råstoff, energiforbruk og transport, og resultatene viser hvordan ulike miljøbelastninger fordeler seg mellom disse fasene. Det viser seg at livsløpsfasen råstoff dominerer påvirkningene fra plastbaserte rørmaterialer, mens bidraget fra duktilt støpejern er nokså jevnt fordelt mellom alle tre livsløpsfaser.

For miljøindikatoren klimaendringer (GWP), som ofte benyttes som en relevant miljøparameter, er det PVC som står for det desidert største utslippet av CO_2-ekvivalenter, etterfulgt av PE. Utslippet fra duktilt støpejern er omtrent halvparten av det fra PVC, mens andelen fra GRP utgjør en drøy fjerdedel.

To ulike presentasjonsmetoder i SimaPro er benyttet for å beregne totalpåvirkningene fra effektkategoriene menneskelig helse, ytre miljø og ressursforbruk assosiert med hvert av rørmaterialene. Begge metoder finner at PE og PVC står for de største miljøpåvirkningene, mens GRP med god margin bidrar med minst.

Sensitivitetsanalyser viser at type elektrisitetsmiks som benyttes kan være avgjørende for analyseresultatet, mens endringer i transportfasen må være betydelige hvis det skal være utslagsgivende. Resultatene endres når rørdiameteren økes, som følge av at plastrørene PE og PVC øker veggtykkelse og vekt i større grad enn de øvrige rørmaterialene.

Den største usikkerheten i studien knytter seg til analysenes inngangsdata, som foreligger i forskjellig form avhengig av kildene som er benyttet. Dette hemmer grunnlaget for sammenligning. Dog er de fleste resultatene tydelige slik at feilmarginen må være vesentlig skal resultatene endres nevneverdig.

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ABBREVIATIONS

DALY = Disability adjusted life years

D_i = Internal diameter

DN = Nominal diameter

E = Egalitarian perspective

EPD = Environmental Product Declaration

GRP = Glass fibre reinforced polyester

GWP = Global warming potential

H = Hierarchical perspective

HDPE = High density polyethylene

I = Individualistic perspective

ISO = International Organization for Standardization

LCA = Life Cycle Assessment / Life Cycle Analysis

LCI = Life Cycle Inventory

LPG = Liquefied petroleum gas

MDPE = Medium density polyethylene

PE = Polyethylene

PN = Nominal pressure

PVC = Polyvinyl chloride

SDR = Standard dimension ratio

SN = Nominal stiffness

VA = Water and sewerage

YLD = Years lived with disability

YLL = Years of life lost

1 INTRODUCTION

1.1 BACKGROUND

Water supply in Norway is regulated through the Drinking Water Regulations, which impose requirements concerning the hygienic safety, quality and quantity of water. The principal focus in the planning of the drinking water distribution network is therefore placed on the consumer's right to sufficient quantities of water that is safe in terms of health, and economic aspects. Sustainability is not used as a criterion (Helse- og omsorgsdepartementet 2001; Sægrov 2010).

The pipe network for the distribution of drinking water and the collection of foul-water and surface water accounts for almost 90 % of Norway's total investment in water and sewerage infrastructure. Pipes, pipe components and manholes therefore represent the majority of the values in the water and sewerage infrastructure sector. The total length of Norway's municipal water pipe networks is around 49,000 km (Myrstad et al. 2011). In other words, taking into account sustainability and environmental considerations in connection with the expansion and renewal of the distribution network could make a substantial difference for the environment.

Sweco Norge is one of Norway's leading consultancy firms within multidisciplinary land use planning. Sweco has an overarching goal of actively contributing to the sustainable development of society. Sweco therefore wished to look more closely at the possibility of choosing pipe materials from a sustainable perspective, an approach which has so far not been considered to any great extent.

1.2 FORMULATION OF OBJECTIVES

Based on the above considerations, the following problem has been formulated:

Might it be appropriate to include sustainability as an assessment criterion in connection with the selection of pipe materials for use in the drinking water network?

Against the background of the above, the purpose of this study was defined on the basis of three key points:

The study will seek to answer the question through

- assessing the environmental sustainability of various pipe materials through the use of life cycle considerations
- comparing the pipes with regard to selected environmental impacts

- investigating which aspects associated with the life cycle of the pipes account for the key environmental impacts

The pipe materials considered in this study are: ductile cast iron, glass fibre reinforced polyester (GRP), polyethylene (PE) and polyvinyl chloride (PVC). These materials were chosen on the basis of their market share in Norway. These four materials account for more than 80 % of the total length of the municipal water distribution network in terms of metres. In connection with the installation of new drinking water pipes today, these pipe materials account for around 98 % of the total pipe length that is installed (Myrstad et al. 2011).

The life cycle analyses consider two pipe dimensions: internal diameter (D_i) 200mm and 600mm. Two different dimensions were studied in order to investigate whether the environmental impacts change significantly as the pipe diameter increases.

The life cycle assessments were carried out using the SimaPro analysis tool. The pipe types chosen for the study are presented in Table 1.1.

PIPE TYPE	DN	D_I	SPECIFICATIONS	SUPPLIERS (SELECTION)
Ductile cast iron	200mm	201mm	C 64* (equivalent to K9)	PAM Duktus
GRP	200mm	208.9mm	PN 16**	APS (Flowtite)
PE100	250mm	204.6mm	SDR 11***	Pipelife Hallingplast Wavin
PVC	225mm	203.4mm	SDR 21	Pipelife Wavin
Ductile cast iron	600mm	605mm	C 40 (equivalent to K9)	PAM Duktus
GRP	600mm	604mm	PN 16	APS (Flowtite)
PE100	710mm	581mm	SDR 11	Pipelife Hallingplast Wavin

TABLE 1.1 – PIPE TYPES ANALYSED IN THIS STUDY

* C = Pressure class, indicates the maximum operating pressure [bar]
** PN = Nominal pressure [bar]
*** SDR = Standard dimension ratio [external diameter/wall thickness]

1.3 STRUCTURE OF THE THESIS

Chapter 2 presents the literature study which forms the basis for the analyses conducted in this study. Here, the topic of sustainability is considered, and findings from relevant life cycle studies are presented. This is followed by the theory chapter, with an introduction to LCA methodology, facts about the water distribution network in Norway, and information concerning the properties and production processes of the four pipe materials which were assessed.

Chapter 4 describes the methods used for the analyses conducted in this study: information acquisition, structure and scope of the analyses, and tools for implementation. A description of the environmental impacts covered by the analyses is also presented here. The following chapter presents the life cycles which form the basis for each of the analyses.

This is followed by the results chapter, which presents selected findings from the analyses. The results are divided into individual and combined results.

In Chapter 7, there follows a discussion of the results and suggestions for further work, before the thesis is concluded with brief conclusions in Chapter 8.

2 LITERATURE STUDY

2.1 SUSTAINABILITY

Global population growth and higher living standards are resulting in the over-exploitation of the world's resources, in addition to land, air and water pollution. As a result of concerns over negative environmental impacts, unfair resource exploitation and the fate of future generations, the United Nation's World Commission on Environment and Development, better known as the Brundtland Commission, directed attention towards sustainable development in 1987. According to the concept, commercial activity must entail the least possible negative impacts for the environment and society, out of consideration for current and future generations (UNESCO 1999).

In 2000, the United Nations adopted eight Millennium Development Goals (MDGs) to eradicate global poverty. MDG 7 is to *Ensure environmental sustainability*, partly through integrating the principle of sustainable development into country policies and programmes and reversing the loss of environmental resources. The 192 Member States of the United Nations have signed the Millennium Declaration, and all the countries concerned have a responsibility to achieve the goals. CO_2 emissions and the protection of terrestrial areas are two of the indicators that are assessed for each of the countries with regard to achievement of the goals (FN 2012b).

Environmental sustainability entails making decisions and implementing measures aimed at protecting the environment. For businesses, the concept is about making responsible choices which will reduce the negative impact on the environment, both by reducing energy consumption and waste, and by developing processes which enable the business to become more sustainable in the future. The focus will be placed on a long-term perspective rather than short-term gain, and in connection with product development, environmental impacts will be assessed over the entire life cycle of the product (NSW 2012).

In Norway, sustainable development has been placed on the agenda in both the public and the private sector, and organisations must strive to minimise their negative environmental impacts. Against the background of the above, environment and sustainability have been chosen as initiative areas in Standards Norway over the coming years. ISO standards 14040 and 14044 present an overview of the use and preparation respectively of life cycle assessments for a product or system (Standard Norge 2008).

Urban water and sewerage systems face challenges regarding the handling of increased water and resource consumption, the renewal of ageing infrastructure, and the installation of new distribution systems in connection with urban development. A sustainable water and sewerage system should serve its purpose and protect both human health and the environment, and non-renewable resources must be consumed as responsibly as possible in a long-term perspective (ASCE 1998). There is an urgent need to develop and implement indicators which enable the quantification and measurability of optimisation parameters, both for existing water and sewerage systems and urban society as a whole (Larsen & Gujer 1997).

A number of studies have referred to the importance of water and sewerage for the overall sustainability of an urban area (Hellstrom D. & Hjerpe 2004; UNESCO 1999). Overarching strategies for improving existing infrastructure and the development of new systems should include environmental aspects at a general level, and life cycle analysis (LCA) can be an important tool when decisions need to be made (Lundin 2002).

2.2 LIFE CYCLE ASSESSMENTS

Life cycle analysis as a method is often used to assess the sustainability of a system, and to identify which aspects of a system's life cycle contribute to the biggest environmental emissions (Windsperger et al. 1999). As regards water and sewerage, there are many aspects which can be assessed, and previous studies have looked at various aspects of water and sewerage technology.

Some studies have considered every stage in an urban area's water supply and sewerage management systems, including water treatment, distribution and sewage treatment (Lundie et al. 2004; Lundin et al. 2000; Qi & Chang 2012). It is often the treatment methods which are the principal focus of such analyses (Friedrich & Buckley 2002). Other studies have looked at drinking water management or sewerage management separately, and considered the systems at an overarching level in order to identify where the potential to increase sustainability is greatest (Ashley & Hopkinson 2002; Savic & Walters 1997).

Studies have also been carried out on urban sewerage systems, including climate-friendly surface water management, with a primary focus on economics (Concrete Pipe Association of Australasia 1996), sustainability (Lundin et al. 2000) or system analysis, with the aim of utilising the results as a basis for decision-making in future planning processes (Piratla et al. 2011). The conclusions drawn in the various studies vary, and there is no consistency as regards recommended solutions, but many have noted that the degree of sustainability in urban water and sewerage systems is a decisive factor in the overall sustainability of an urban area (Filion et al. 2004; Lundin 2002; Lundin & Morrison 2002; Penagos 2007; Savic & Walters 1997).

Pipe materials

Various pipe materials in water and sewerage networks have been analysed with regard to sustainability on a number of occasions (Andersson 1998; Dennison et al. 1999; Venkatesh et al. 2009; Windsperger et al. 1999). The analyses have adopted different approaches, system boundaries and functional units. They are usually analyses of sewerage pipes, including surface water pipes and foul-water pipes (Andersson 1998; Venkatesh et al. 2009). A number of studies have considered both water and sewerage pipes. The pipe materials PVC and concrete occur most frequently in the analyses (Andersson 1998; Windsperger et al. 1999).

Many studies have been initiated by pipe manufacturers wishing to compare their products with competing pipe types available on the market. Previous studies have not produced unambiguous results; on the contrary, the pipe materials which perform well or badly vary. There has also been no great swing in either a positive or negative direction. It is noted that the results are less creditable if they are in favour of the client (Windsperger et al. 1999), as has been the case on a number of occasions (Andersson 1998; Borealis AG 2008; Concrete Pipeline Systems Association 2001; Howard 2009; Windsperger et al. 1999).

Comparative studies

A British study (Dennison et al. 1999) has looked at two different pipe materials for water distribution, ductile cast iron and polyethylene, and compared these two materials with regard to their environmental impact throughout the life cycle of the pipes, e.g. energy consumption and global warming potential (GWP). The study concluded that the protective zinc layer on cast iron pipes provides a significant environmental contribution due to the energy required during the manufacturing process. Whereas for the PE pipe, it is the production of polyethylene that has the greatest negative impact. It was also found that most environmental loads for both pipe materials originate from processes linked to raw materials, rather than pipe manufacture and use. This means that the negative environmental impacts associated with a water distribution system can be reduced considerably by using pipes which are manufactured from raw materials with less environmental impact (Friedrich et al. 2007). The study did not result in a recommendation of one material over the other.

Another study (Recio et al. 2005) looked at the most frequently used pipe materials for drinking water and foul-water distribution, and considered energy consumption and CO_2 emissions associated with all the phases in the life cycle of the pipes. On the drinking water side, PVC, PE and ductile cast iron were analysed. The study found that the greatest proportions of the energy consumption and CO_2 emissions are linked to the pipes' use phase, defined as a 50-year lifetime with pump operation and normal maintenance. The second biggest contribution comes from the processing of the raw materials used in each of the pipe manufacturing processes. The results of the analysis are presented relative to PVC, which comes out best as regards both parameters. PE is marginally inferior as regards both energy consumption and CO_2 emissions (1.4 and 0.4 % higher respectively). Ductile cast iron comes out worst as regards energy consumption, which is 56 % higher than the reference material PVC, and CO_2 emissions which are 51 % higher, although this concerns cast iron without any recycled raw materials.

A recently published study (Du et al. 2012) looked at six different materials used in water and sewerage pipes: PVC, HDPE, ductile cast iron, grey cast iron, concrete and reinforced concrete. The pipe materials were analysed with regard to contributions to potential global warming through the four life cycle phases of pipe manufacture, transportation, installation and use. The materials were also analysed with regard to increasing diameters, with the aim of seeing how the impacts change with diameter. In the case of diameters of up to 710mm, cast iron pipes perform worst, whereas from diameters of 760mm upwards, PVC gives the greatest contribution. Concrete performs best for all analysed pipe diameters. Of the life cycle phases analysed, it is the manufacturing phase which dominates the impact for all six pipe materials, and the transportation phase which is of least importance.

Two relevant studies, a Swedish study carried out by CIT Ekologik, Chalmers Industriteknik (Andersson 1998), and an Austrian study initiated by the European Plastic Pipe and Fitting Association (Windsperger et al. 1999) looked at a number of sustainability analyses of different pipe materials and compared them. These studies reviewed many aspects associated with LCA analyses and the way in which these aspects are considered in the various reports.

Both the studies are considered to be relevant, as they identified key factors relating to life cycle assessments, analysis methods and structure. A selection of these factors is presented in the following sections; other references are given.

Method

When conducting life cycle assessments of a number of products with the aim of comparing them, it is vital that the functional unit is selected specifically and appropriately. This will ensure that the products can be compared as fairly as possible, provided the basic requirements for product function are met. In studies which have considered various pipe materials, the functional unit is often chosen as 1m, 100m or 1000m of pipe of different dimensions and qualities (Spirinckx et al. 2011); alternatively, transportation capacity is expressed as volume per time unit used (Filion et al. 2004; Herstein & Filion 2010).

Life cycle analyses must have a defined scope, and the system boundaries that are chosen determine which ecological impacts will be included in the analysis. These should therefore be well-justified. If too much is included, it will result in an unrealistically high impact, whereas using boundaries that are too narrow could result in some relevant processes being excluded and the overall impact being underestimated. The system boundaries should be chosen on the basis of the purpose of the study, and the structure of the analysis should strive to find alternatives with the least possible environmental impact in one or more process stages without neglecting any negative impacts in other sub-stages (Lundin & Morrison 2002). In principle, an analysis should cover as many material and energy flows as possible, both upstream and downstream of manufacture (Penagos 2007). Transportation at every stage of the life cycle, including the transportation of raw materials, products and discarded waste, should be included. Excluding transportation stages could result in products with long-distance transportation elements being favoured, as they will often entail a larger emissions contribution than elements which are transported shorter distances, although the means of transportation used is also a factor.

The choice of energy limits and energy mix will also have a major impact on the outcome. Among other things, excluding external energy sources will result in products which consume external energy being favouritised, and result in lower overall emissions than is actually the case. The choice of energy mix could be entirely decisive for the outcome of an LCA analysis, as the differences in emissions from different energy sources is often considerable. Different energy sources give different emission contributions as regards NO_x, SO_x etc., as well as greenhouse gases which increase the potential for global warming (Stokes & Horvath 2005).

In many analyses, the installation process is considered to be identical for all pipe materials, but this means that factors such as pipe thickness and weight are ignored, when in reality they may be decisive both as regards the choice of installation method and other wastage in the form of offcuts at the installation site. Different requirements are also imposed on the groundworks for the various pipe materials. In the Swedish study (Andersson 1998) it is claimed that the installation phase causes the greatest environmental impact as regards sewerage pipes. On the basis of this, it may be considered unreasonable to assume that the process is identical for all materials. On the other hand, two recent studies considered pipe installation as a separate life cycle phase and concluded that the impacts from this phase, regardless of the pipe material, are insignificant. One study (Recio et al. 2005) decided to completely ignore energy consumption during this phase, as it is assumed that pipes of equal diameter will have approximately equal energy requirements. The other study (Du et al. 2012) calculated climate change in the form of CO_2 equivalents, and found that the impacts from the installation phase for ductile cast iron, PE and PVC are less than half a percent of the total impacts in all three cases.

The environmental impact from the pipes' use phase varies in scope with factors such as maintenance and cleaning requirements, defects and deficiencies, and damage and leaks. As these are aspects which have been given little consideration as regards concise data, it may be appropriate to only refer to them qualitatively, and possibly include them in a concluding sensitivity analysis.

The choice of lifetime is an important factor which may be decisive in terms of which pipe material comes out best. This varies between the various studies, and it might appear that the outcome is fairly proportional to the chosen lifetime. If the lifetime of the product is not taken into consideration, all the materials will be deemed equal with regard to duration. The disposal of pipes after the end of their useful life is also considered differently in the various studies, and may be decisive for the outcome. It was for example noted for a number of the cases in the Austrian study that plastic pipes would have performed better had a higher recycling rate been used for the plastic.

If a study is to be used as a reference, it is crucial that the results can be verified. In order to underpin the credibility of an analysis, it should be possible to study all links in the structure of the life cycle, and to consider all the values used in the calculations. Such transparency should enable the reader to assess the scope of the analysis, the extent to which obligatory steps have been taken into account and whether anything has been excluded.

Results

A selection of results from the above studies are presented in the table below. It is worth noting that the results are taken from life cycle analyses with differing scopes with different system boundaries and underlying data, and the figures may therefore not be comparable across the rows. The important consideration is the difference between the values within the rows, which says something about how the pipe materials perform relative to each other in the respective analyses.

A number of the studies are relevant for comparison with the investigations carried out in this study, but none can be compared directly, as all the other studies are more comprehensive as regards the scope of the life cycles.

TABLE 2.1 – RESULTS FROM LIFE CYCLE ANALYSES OF DIFFERENT PIPE MATERIALS

AUTHOR	**YEAR**	**ENVIRONMENTAL IMPACT**	**CAST IRON**	**PE**	**PVC**	**GRP**
Du et al.	2012	GWP [tonnes CO_2/km pipe]	472	218	318	-
Piratla et al.	2011	Energy consumption [MJ/kg pipe]	34.4	74.9	75.2	-
Venkatesh et al.	2009	GWP [kg CO_2/kg pipe]	3.41	2.33	2.36	-
Recio et al.	2005	Energy consumption [kWh/3m pipe]	1620	1055	1041	-
		GWP [kg CO_2/3m pipe]	681	454	452	-
KIWA	1992	Energy consumption [GJ/100m pipe]	36	-	6.9	6.9

- = not analysed in the study concerned

3 THEORY

3.1 LIFE CYCLE ANALYSES – LCA

A life cycle analysis is a comprehensive method for assessing the environmental impacts of a product (or a service) throughout its entire life cycle. The term 'life cycle' is intended to cover all stages in a product's lifetime, *from cradle to grave*. A life cycle analysis therefore looks at the environmental impact of a particular product from raw material extraction and material production via transportation stages, use and maintenance, through to waste management/disposal. If appropriate, the life cycle phases can be limited to cover the stages *from cradle to door*, i.e. through until the product has been manufactured and is ready for use. This is often appropriate when it is difficult to obtain good data about a product's use phase. A final alternative is to look at the life cycle *from cradle to cradle*, if at the end of its use phase the product is recycled and used in the manufacture of a new product, rather than being processed as waste.

A life cycle analysis can provide a general overview of relevant environmental aspects associated with a product, and help to determine where in the life cycle the most important impacts occur. This is done by including relevant material and energy flows both in and out of the system, and evaluating them with regard to potential environmental impacts. Using this method increases the likelihood that the most sustainable solutions can be promoted and developed further (Standard Norge 2006a).

Standards for environmental management systems are covered by the ISO 14000 series, and the procedures for LCA are set out in ISO 14040 and 14044, both dating from 2006. In order for an analysis to comply with these standards, a number of requirements must be satisfied. If the analysis is to be published externally, there are specific criteria which must be met, e.g. there is a requirement for verification by an external third party, which will come in at an early stage in the process and ensure an honest process. The four main steps in the LCA analysis are described in detail in ISO 14044. These steps are discussed in their respective sections below, and illustrated in Figure 3.1 on the next page.

DEFINITION OF OBJECTIVE AND SCOPE

The purpose of the analysis and its scope are determined in this step. The first aspect to clarify is the product system's *functional unit,* i.e. *a quantified performance for a product system for use as a referent unit.* The entire analysis is built around the functional unit. This must be defined so that the analysis is built around the product's *function* insofar as is possible, and often includes a time aspect and a geographic or area-related delimitation. The objective of the LCA analysis is furthermore linked to the scope of the study, partly by defining what is to be included and which processes can be excluded, as well as which environmental parameters are to be analysed for (Baumann & Tillmann 2009). If the analysis is being carried out in order to compare different products with the same function, as in the case of this study, it may often be appropriate to exclude phases in the life cycle with a comparable impact picture for the respective products.

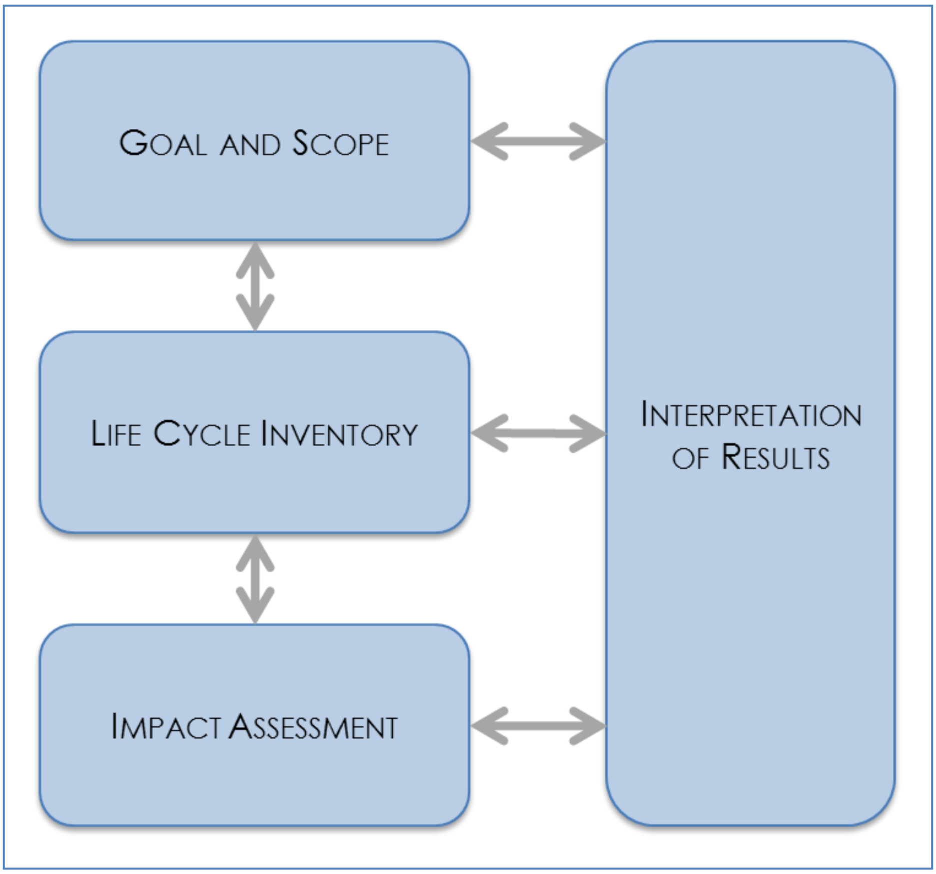


FIGURE 3.1 – THE FOUR STEPS IN A LIFE CYCLE ANALYSIS (AFTER BAUMANN & TILLMANN 2009)

LIFE CYCLE INVENTORY

In the life cycle inventory, a system model is constructed in accordance with the defined functional unit. The inventory consists of preparing an inventory of the product system's flows from and to nature; respectively the inflow of energy, raw materials and water, and emissions to the atmosphere and the terrestrial and aquatic environments. Using these input and output data, a flow model is created for the technical system, which provides an overview of the system's flows. The model can be illustrated through a flow chart showing the relevant activities during the product's lifetime and the associated underlying processes. The flow chart can be used as an aid in obtaining an overview of the analysis' system boundaries and which processes should be taken into consideration (Baumann & Tillmann 2009).

All necessary input and output values linked to activities within the system boundaries are imported before the complete model can be constructed. The data must be adapted to the chosen functional unit, and the results of the life cycle inventory will then provide information on elementary flows to and from the environment for all unit processes in the study, directly related to this functional unit. Depending on the system boundaries, there may be several hundred flows.

It may be a challenge to gain access to all the data that is needed for the flows which flow in and out of the *technosphere*, defined as the modelling of material in the form of production processes, product systems and transportation processes which exist within society (Goedkoop et al. 2010). These values must often be obtained from secondary, more general sources, e.g. national databases or data sets in analysis tools. In this regard, caution must be exercised to ensure that any secondary sources that are chosen are sufficiently relevant. Figure 3.2 shows what the system boundaries of a product can look like.

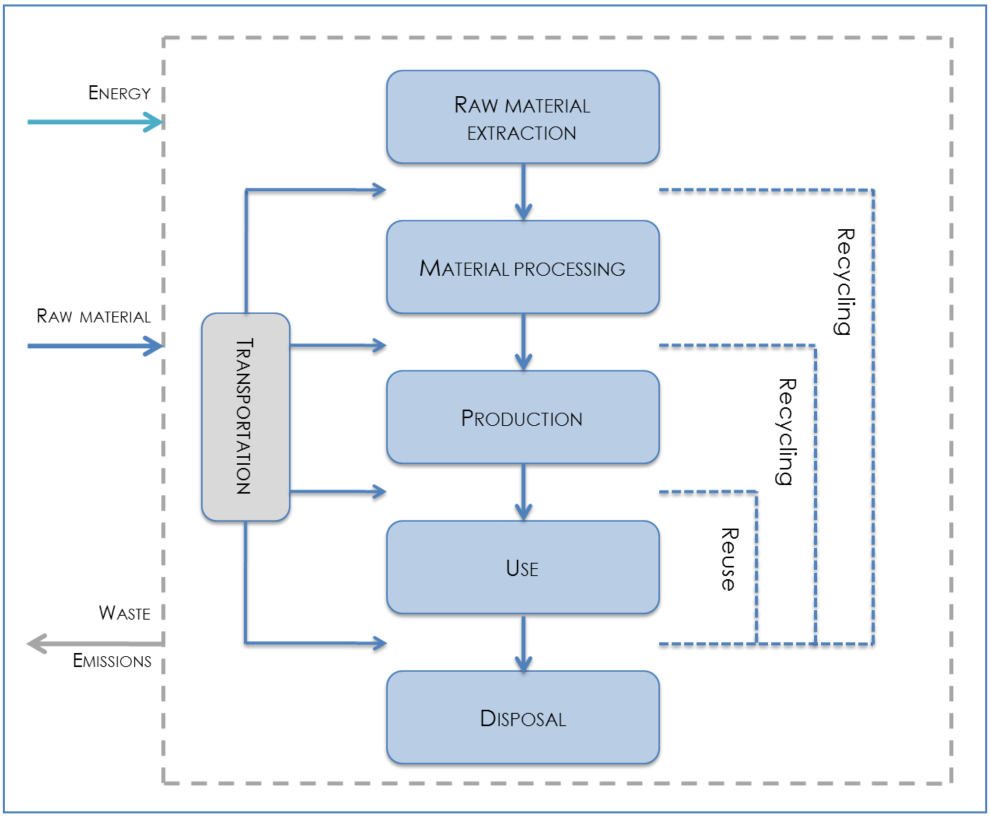


Figure 3.2 – Schematic illustration of system boundaries in a life cycle assessment (after Baumann & Tillmann 2009)

IMPACT ASSESSMENT

The aim of this step is to put the results of the life cycle inventory into an environmental perspective, by looking at the potential environmental impacts to which different parameters can contribute. Here, the importance of emissions and resource consumption linked to the functional unit is evaluated. The impact assessment is three-fold: First, all the environmental loads/parameters are *classified* in relation to the environmental impacts to which they contribute. The relative impact of the various environmental loads within each impact category is then *characterised*. Finally, the results of the impact categories are *weighted*, resulting in a one-dimensional total impact. This can be done by normalising measured impacts internally within each impact category on the basis of formalised procedures for weighting. Such a procedure could for example be based on political environmental targets. The total impact can also be determined using statements from an appointed panel of experts or be based on qualitative reasoning (Baumann & Tillmann 2009).

A distinction is often made between local, regional and global impacts, as well as the time perspective on the impacts. Table 3.1 lists various environmental impacts under their respective impact categories.

TABLE 3.1 – SELECTED POTENTIAL IMPACTS ASSOCIATED WITH A PRODUCT
(AFTER BAUMANN & TILLMANN 2009)

HUMAN HEALTH	**ECOSYSTEMS**	**RESOURCE DEPLETION**
Toxic effects	Global climate change	Energy
Working environment	Ozone depletion	Materials
Psychosomatic effects	Acidification	Water
Noise	Eutrophication	Areas

INTERPRETATION

This is the final step in the analysis. Here, the findings from the life cycle inventory and the impact assessment are placed in context with the goals and scope defined in the first stage. The results are identified, quantified, tested and evaluated systematically. Finally, the results are summarised to form a set of conclusions and recommendations. Validity, uncertainty and any weaknesses associated with the analysis should be specified here (Standard Norge 2006b).

3.2 THE WATER PIPE NETWORK IN NORWAY

In Norway, four main types of pipe material are currently being used in the installation of new potable water pipeline networks: ductile cast iron, glass fibre reinforced thermoset plastic, polyethylene and polyvinyl chloride. This differs to some extent from the distribution of materials used in the existing pipe network, as some pipe materials are relatively new and becoming more widespread in extent, while others are being phased out (Myrstad et al. 2011). The distribution of pipe materials in the Norwegian water pipe network, based on information from 2008, is shown in Figure 3.3.

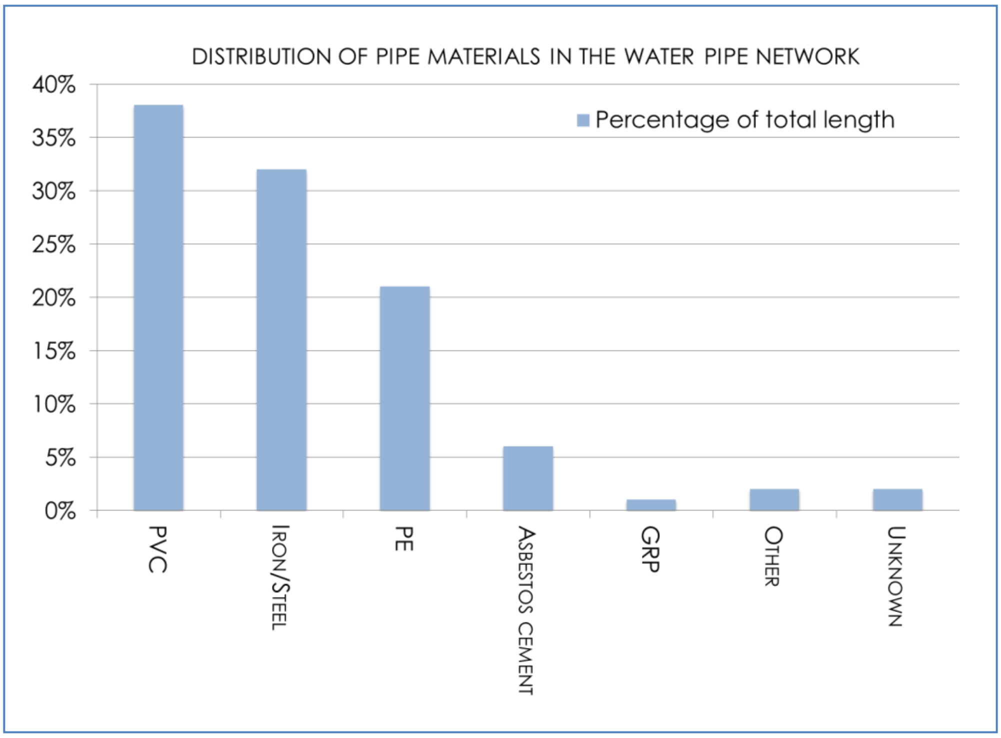


FIGURE 3.3 – DISTRIBUTION OF PIPE MATERIALS USED IN THE NORWEGIAN WATER PIPE NETWORK AS OF 2008 (AFTER MYRSTAD ET AL. 2011)

The Norwegian foundation *VA/Miljøblad* (Water and Sewerage/Environment Guideline) was founded by the Norwegian Association of Municipal Engineers and Norwegian Water (*Norsk Vann*) with the aim of producing recommended norms for technical water and sewerage solutions. The environmental guidelines were prepared on the basis of requirements laid down in European standards. Water and Sewerage/Environment Guideline No. 30 (2010) – *Choice of pipe materials* (*Valg av rørmateriell*) describes the following functional requirements:

"The pipe material must be resistant to all internal and external stresses of a physical and chemical nature within a design lifetime of at least 100 years. The most relevant stresses are internal pressure, pressure surges, hydraulic forces in bends, transitions, T-

pipes, internal erosion, thermal stresses, frost, external soil pressure, traffic loads, point loads and ground settlement. In the case of water pipes, the pipe material must satisfy the hygienic requirements laid down in the Drinking Water Regulations."

In other words, materials for use in pipe networks must posses technical properties such as corrosion resistance, strength, flexibility and resistance to external loads. The properties vary between different pipe materials, and factors such as ground conditions and design traffic loads can be important when choosing pipe types. Certain technical properties can therefore often be decisive as regards material selection when new pipe sections are being installed. Weight and ease of handling, installation method and requirements concerning ground conditions are additional aspects which must be assessed. It is also important that the pipes are compatible with existing solutions and that there are systems in place for the future connection of branch pipes (VA/Miljø-blad 2010). Figure 3.4 illustrates the estimated distribution of pipe materials in connection with the installation of new drinking water pipes.

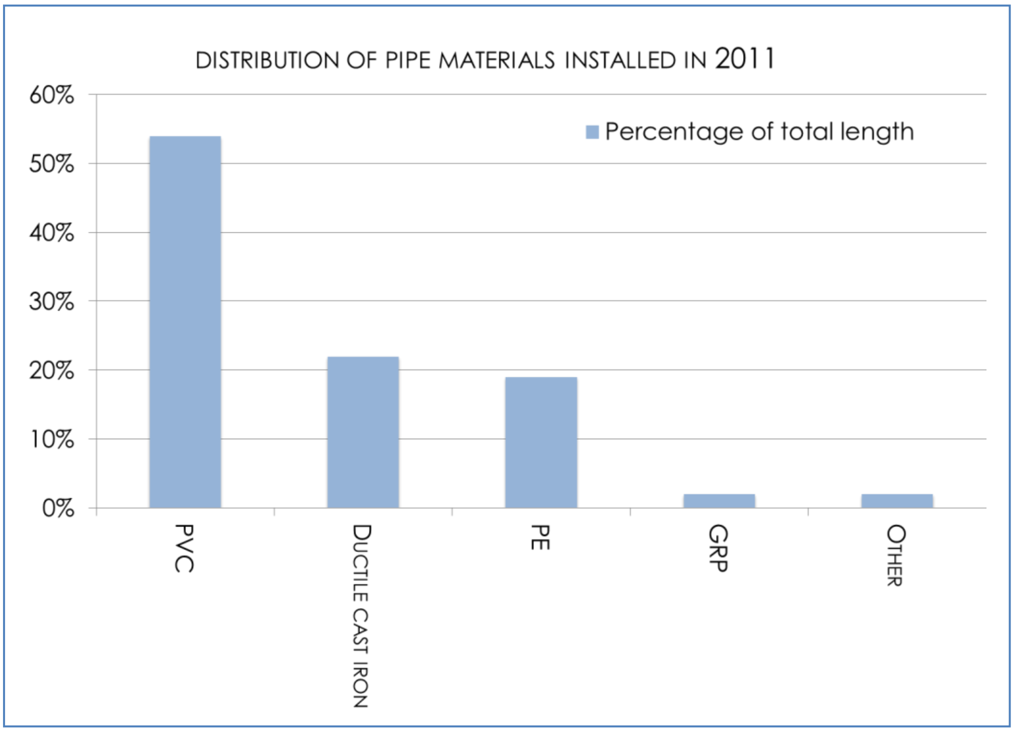


FIGURE 3.4 – ESTIMATED DISTRIBUTION OF PIPE MATERIALS IN CONNECTION WITH THE INSTALLATION OF NEW DRINKING WATER PIPES (AFTER MYRSTAD ET AL. 2011)

A holistic assessment based on the above points, as well as economic considerations, availability and delivery reliability, is used as a basis in the choice of pipe materials (Sægrov 2010). It does not currently appear to be Norwegian practice to take into account environmental sustainability when choosing pipe materials.

SPECIFICATIONS

Conditions in and around the trench, such as depth, surrounding material, frost and traffic loads, may result in substantial loads being imposed on the pipes in the trench. Ductile cast iron pipes, which are rigid, meet these loads by absorbing stresses in the pipe wall. Flexible pipe materials, including plastic, interact with the surrounding materials and must therefore be laid on well-compacted materials.

Mechanical strength

The drinking water pipe network is pressurised, i.e. the water is distributed with the aid of an operating pressure, which is normally between 1.5 and 8.5 bar throughout the delivery zone. Certain requirements are imposed on the pipes that are used; they must withstand both internal pressure and external stresses.

The mechanical strength of a pressurised pipe depends on a number of factors relating to both internal and external load:

- The ability to withstand internal pressure
- The ability to withstand external pressure in a radial direction, type of soil load and traffic load
- The ability to withstand external loads in a longitudinal direction.
- The ability to withstand external, mechanical surges, often expressed as the ability of the pipe to withstand impacts without cracking: toughness

The mechanical properties of pipe materials can be described as elastic/viscoelastic or brittle and tough. Elastic materials, including cast iron, exhibit a linear progression upon loading and unloading – an unambiguous relationship between stressing and extension. Viscoelastic materials increase the deformation over time under constant loading (Moser & Folkman 2008).

Plastic materials are divided into two groups: thermoplastic and thermoset plastic. Thermoset plastic is soft plastic which can be moulded using heat treatment. It can be moulded and remoulded repeatedly without any adverse effect on its quality. PE and PVC fall under this category. The other type is thermoset plastic, which does not soften upon heating and can therefore not be remoulded through heat treatment. GRP pipes are made from such thermoset plastic (Ødegaard 2012).

3.3 PIPE MATERIALS

DUCTILE CAST IRON

Use

Ductile cast iron has been available on the market since 1960, following the discovery that adding magnesium to grey iron changes the properties of the iron from brittle to tough. This opens up the possibility of the wider use of cast iron in the water and sewerage network. The material is now one of the most widely used materials in the Norwegian water supply network. Ductile cast iron pipes rarely fracture, as the material is durable and able to withstand substantial pressure loads. However, it is vulnerable to perforation as a result of corrosion, and must be protected against this. Cement mortar is normally applied internally, along with epoxy compounds on the outside of the pipe (Mosevoll & Oddevald 2010). Cast iron pipes are not produced in Norway, but are supplied by major European manufacturers in Germany and France. Around 18,000 tonnes of cast iron pipes are supplied to Norway every year.

Requirements

All ductile cast iron pressurised pipes for Norwegian use are manufactured according to NS-EN 545:2006. A pressure class corresponding to K9 in the abovementioned standard must be selected. A new edition of the standard was published in 2010, but this is not recognised in the Norwegian market, or anywhere else in Europe, as it entails reduced requirements concerning wall thickness, which reduces the strength of the pipes. The radial stiffness of the material is proportional to the cube of the wall thickness, and the dimensions laid down in the 2006 edition are therefore considered to offer greater certainty. Other changes to the new standard relate to requirements concerning pipe marking, and it generally operates with more variants of pipe, resulting in a lack of clarity according to some (Egeberg 2012). It should be noted that this is a guideline standard, and not a regulation or law. As the K classification is still preferred in Norway today, it was decided to analyse ductile cast iron pipes of K9 quality. However, it should be noted that the 2010 standard with pressure classes of type C rather than K classes entail a considerable reduction in weight for the pipes, which might give a more positive outcome if analysed.

Cast iron is susceptible to corrosion, to a greater or lesser extent depending on ground conditions, and must be protected accordingly. Internal protection must consist of a cement mortar lining, with blast furnace slag cement. Design and thickness in accordance with the description in NS-EN 197-1. A 200g/m^2 zinc coating must be applied between the pipe wall and the protective layer. A PE shrink sleeve must also be supplied by the manufacturer for each pipe length, which is placed over the sleeve joint (VA/Miljø-blad 2007a).

Manufacture

By weight, cast iron pipes consist of approx. 93% iron, 4% graphite, and 3% other metals. By volume, the proportion of graphic amounts to almost 15%, which contributes to the good sound-damping properties of cast iron pipes.

During the first stage of pipe manufacture, pig iron, scrap iron and other recycled metals are treated at around 1500°C in a cupola furnace. Air is blown in from the bottom and helps to heat the solid substances, which then sink downwards in the furnace. On the way down, the mass changes in a number of stages; it is heated to the combustion point, melts and absorbs carbon, which helps to make the iron stronger. At the bottom of the furnace is the liquid iron covered by slag which protects the iron mass from undesirable oxidation. The liquid mass is analysed for its constituent components, e.g. carbon, silicon, manganese and magnesium. The values are assessed against the desired composition, and various additives are added in accordance with this formula. The substances and amounts that are added thus depend on the properties of the scrap metal in the molten mass.

Magnesium in gaseous form promotes the formation of spheroidal graphite and is an important component in cast iron, as this reaction helps to make the iron tough rather than brittle. Additional magnesium must therefore be added if the original quantity in the molten mass is less than the required value. The temperature must be maintained fairly accurately at 1500°C in order for the required toughness to be achieved. At temperatures above or below a range of approx. 20°C, the cast iron will still become brittle, as the spheroidal reaction between the graphite and magnesium requires a very specific temperature. Similarly, magnesium must be added in the same temperature layer in connection with any remelting of ductile cast iron, as the iron will otherwise become brittle (Mosevoll & Oddevald 2010; Ødegaard 2012).

The final step to be carried out before the actual pipe moulding is the addition of inoculants to the molten mass to prevent the formation of unwanted components.

The pipe is moulded in the next step. This takes place in a rotary casting mould, where the metal stiffens during continuous cooling. The quality of the pipes is checked systematically, partly through hydrostatic tests, visual inspection and examination of the metal's structure and the pipes' dimensions. During this control phase, pipes can sometimes be rejected. Rejection will result in an entire consignment of new pipes being discarded. The pipes can then be returned to the manufacturing process as scrap metal, either via a scrap dealer or directly. Figure 3.5 shows a cast iron pipe being moulded in a rotary casting mould.

FIGURE 3.5 – A CAST IRON PIPE TAKES SHAPE (DUKTUS.COM 2012)

When the pipes are moulded and dimensioned, internal and external coatings are applied. This protects the pipes from corrosion, both from the water which is to be transported on the inside and from surrounding materials. In the case of pipes which will be used for distributing drinking water, specific requirements are imposed concerning protective coatings in order to avoid any adverse effect on the hygienic properties of the drinking water. Cement mortar is used internally. This is hygienised at high temperature.

The final step in the manufacturing process is the addition of elastomers to the joints, which ensures that the joints remain sealed throughout the 100-year life of the pipes. It is important that the seals do not leak while the pipe is in use, and different elastomers are chosen depending on the required properties in the trench. Pipe sections can shrink or expand over time, depending on the temperature and the degree of compression, and without elastomers, these factors will determine whether or not the joints remain tight in the long term (Egeberg 2012; Svendsen 2012).

GLASS REINFORCED POLYESTER – GRP

Use

GRP stands for 'Glass Reinforced Polyester' and is used as a designation for glass reinforced thermoset plastic. GRP pipes were previously designated using other abbreviations such as GUP (Glass Reimbursed Unsaturated Polyester) and FRP (Fibreglass Reinforced Plastic), but the material is the same. Under current standards, the designation 'GRP' is now used.

GRP pipes are often used for large supply and transfer pipes for water, as they are economically competitive in dimensions from 500mm upwards. The average pipe dimension that is manufactured is 1100mm (Ressourcen Management Agentur GmbH 2011). The pipes are built up from glass fibre threads and thermoset plastic, which gives strength and has good corrosion properties (Sægrov 2010).

Requirements

All GRP water supply pipes must be manufactured as described in NS-EN 1796. Specific requirements also apply to sealing rings which come into contact with drinking water. These must be of synthetic quality and have good ozone and ageing properties (VA/Miljø-blad 2003).

Manufacture

The pipe dimensions chosen for analysis in this study (D_i 200 and D_i 600) are smaller than the majority of GRP pipes that are manufactured, which have an average pipe diameter of 1100mm. It is unusual for this material to be used for diameters of less than 500mm in Norway, and only one factory in Europe manufactures pipes with diameters of the order of 100-300mm. This takes place in a discontinuous process with the manufacture of pipe lengths of 6 metres. The manufacturing process is otherwise identical to the continuous process described in the next section. Other manufacturing processes for GRP pipes (centrifugal moulding and cross-winding) are not discussed further here, as the methods are respectively used to manufacture pipes with reduced pressure capacity and pipes which are not used within water and sewerage (Nordiske Plastrørgruppen Norge 2011).

GRP is a composite material, and GRP pipes are composed of three main raw materials: glass fibre, polyester and sand. Glass fibre in its cut and continuous forms forms the pipe's reinforcement, in all directions and in the radial direction respectively. This gives the pipes strength. Resin in the form of polyester, usually orthophthalic acid polyester, binds the glass fibre reinforcement and sand together. The sand is used as a filler in the core of the pipe. The structure of a pressure pipe is shown in Figure 3.6:

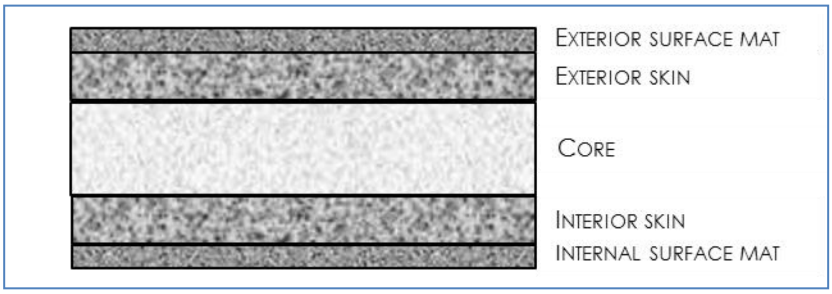


Figure 3.6 – Structure of a GRP pipe (translated from a figure from Flowtite Norway)

The pipes are manufactured using what is known as a continuous winding process. The manufacturing process takes place around an advanced core through the external application of materials, building up the layers as shown in the figure above. The first layer to be produced is the internal surface, which consists of a polyester-rich liner reinforced with some glass fibre, and a surface mat which forms the pipe's contact surface with the medium being transported.

The core is surrounded by structural layers on both the inside and outside. These layers contain the majority of the reinforcement which gives the pipes their strength, particularly the continuous glass fibre in the radial direction, which helps to make the pipes resistant to internal pressure and external loading. The core gives the pipes their thickness and mostly consists of cut glass fibre and quartz sand bound with polyester. The polyester hardens due to the temperature of the manufacturing process, which reaches 130°C. This results in good hardening with low residual values for various substances in the finished laminate. The pipes taken on their final form as the polyester hardens in a cross-bound molecular structure. Unlike thermoplastics, GRP pipes cannot subsequently be remoulded through melting. The manufacturing method which is described has a high capacity and produces pipes with good pressure properties (Hausberg 2009; Hausberg 2012).

POLYETHYLENE – PE

Use

Polyethylene is a synthetic thermoplastic and is the most widely manufactured type of plastic to be manufactured on a global basis. Polyethylene is a robust material which is primarily used within the water and sewerage sector for pressurised pipe systems. Under normal circumstances, PE is considered to be the most abrasion-resistant material (Sægrov 2010).

PE pipes are often used as underwater pipes and under difficult installation conditions in trenches, as they can be welded together to form long continuous pipes.

PE as a pipe material is available in both medium density (MDPE) and high density (HDPE) forms. In pressure pipes, these materials are designated PE 80 and PE 100 (Nordiske Plastrørgruppen Norge 2011). PE 100 pipes can withstand higher pressures than PE 80 pipes of the same dimensions, wall thickness and design factor (Pipelife 2008). The pipe material analysed in this study was PE 100.

Requirements

PE pressure pipes are manufactured in accordance with NS-EN 12201-2 and 3 (VA/Miljø-blad 2007b). There is no Norwegian approval system for materials which are to be used in contact with drinking water. Norwegian PE pipes are manufactured in accordance with the Danish approval scheme, which is based on requirements laid down in the Drinking Water Regulations. Pipes used in Norway are therefore marked as Danish standard (DS-marked) (Pipelife 2008).

Manufacture

PE is exclusively manufactured from organic matter and is produced through the polymerisation of ethylene gas. Ethylene gas is produced by refining petroleum or natural gas. The ethylene gas is polymerised through a continuous reaction, in other gaseous or slurry form. This process involves the addition of substances which give the plastic the required properties, e.g. antioxidants are added to stabilise the plastic. The end product of the process is polyethylene in granulate form.

PE pipes are manufactured in an extruder. The raw material is PE granulate, which already contains the necessary additives from the abovementioned process. The extrusion takes place at a mass temperature of just under 200°C. At this temperature, the plastic is viscous and easy to mould into a circular product through an extruder nozzle. The material then enters a calibration unit for cooling and the determination of dimensions. The pipes are manufactured in continuous lengths without sleeves (Nordiske Plastrørgruppen Norge 2011).

POLYVINYL CHLORIDE – PVC

Use

PVC was the first plastic to be used in pipe production back in the 1930s. It is a strong, lightweight material and is often used for water and sewerage pipes both in Norway and internationally. PVC is now the market-leading material for water pipes of up to 400mm in diameter in Norway (Nordiske Plastrørgruppen Norge 2011).

It is claimed that the manufacture, use and disposal of products containing PVC can cause substantial harm to the environment and health. For this reason, PVC is a relatively controversial material, and its negative impacts are recognised by both public authorities and research institutions around the world. Restrictions on the use of PVC are in place across much of Europe, and a number of countries have ambitions to reduce the use of this material (Thornton 2001). However, this has resulted in the initiation of a number comprehensive life cycle studies, which concluded that PVC products are neither superior nor inferior to other alternatives as regards a broad spectrum of environmental and health risk assessments (Howard 2009).

Requirements

PVC pipes must comply with technical provisions in accordance with NS-EN 1452-1, 2 and 3. The pressure class for water pipes must be at least PN 12.5, which corresponds to an SDR value of 21 (VA/Miljø-blad 2001).

Manufacture

Ethylene gas is refined from petroleum or natural gas, while chlorine gas is synthesised from sea salt using high-energy electrolysis. These two gases are the main components in PVC. Ethylene dichloride is produced by linking chlorine and ethylene together in a chlorination process. Hydrogen chloride is a by-product in this reaction, and combined with more ethylene, ethylene chloride is produced in an oxychlorination process. The ethylene chloride compounds are then converted into vinyl chloride monomers via pyrolysis. Finally, the vinyl chloride monomers are linked together to form polyvinyl chloride. The product is often in powder or granulate form.

Chemicals are added to polyvinyl chloride in its pure form, including stabilisers, plasticisers, colouring agents etc., in order to produce a plastic with the required properties. PVC is not particularly useful in its purest form; it is stiff and brittle, and degrades upon exposure to ultraviolet light (UV rays). Additives must therefore be added to ensure that the plastic is flexible and durable. The final stage in the process is to mould the plastic into the finished pipe product (Nordiske Plastrørgruppen Norge 2011; Thornton 2001).

Table 3.2 presents an overview of selected positive and negative properties associated with the various pipe materials, taken from similar tables in the literature (Nordiske Plastrørgruppen Norge 2011; Ødegaard 2012). As is apparent from the table, environmental aspects are completely absent.

Table 3.2 – Overview of selected positive and negative properties of different pipe types
(after NPG 2011 and Ødegaard 2012)

Pipe type	Advantages	Limitations
Ductile cast iron	• Corrosion-resistant with corrosion protection • Strong material • Withstands substantial external loads • Withstands temperatures >40^{o}C • Flexible, simple jointing systems	• Vulnerable to corrosion if unprotected • High weight
GRP	• Low weight and long pipe lengths • High strength, highest elastic modulus of the plastic pipes • Mechanical properties remain unchanged between -50 and 35^{o}C • No UV protection necessary for installations above ground level • Very low thermal expansion coefficient • Good hydraulic properties • Very corrosion-resistant	• Susceptible to damage by impacts and surges • Vulnerable to large point loads • Centrifugally cast pipes may have reduced capacity to withstand high pressures • Low permitted extension
PE	• Low weight, long pipe lengths, simple cutting • Good impact-resistance, even at very low temperatures • Very high flexibility • Load-bearing joints with welding • Very good hydraulic properties • Very corrosion-resistant • Tight against water/air leaks over time	• Considerable length extension • Need for load-bearing coupling points • Capacity to withstand pressure is reduced at temperatures above 20oC • Soft material, must be handled carefully in order to prevent scratches/damage
PVC	• Low weight, long lengths and simple to cut • Low thermal expansion • Flexible pipe which withstands most movement in the pipe zone without fracturing • High elastic modulus, results in good strength and capacity • Good hydraulic properties • Corrosion-resistant • Tight joints	• Reduced impact strength below -10oC • Point loads can result in brittle fracture • Limited capacity to withstand repeated pressure surges

4 METHOD

4.1 MAPPING

DATA REQUIREMENTS

The following data are considered to be required in order to carry out satisfactory analyses:

- General and valid information concerning all raw materials
- Site-specific information concerning energy consumption in the respective pipe manufacturing processes
- Specific information concerning transportation distances and modes of transportation
- General information concerning emissions associated with transportation
- Geographically representative energy mix for all activities

SOURCES

The input data used in the analyses were obtained from relevant manufacturers and suppliers in Norway, following meetings. The questions which were distributed in advance of these meetings are presented in Appendix B. Suppliers were selected on the basis of their size in Norway and the fact that they supply pipe dimensions of relevance for this study. An overview of manufacturers and suppliers is presented in Table 4.1.

TABLE 4.1 – OVERVIEW OF SOURCES USED FOR THE LIFE CYCLE ANALYSES OF THE VARIOUS PIPE MATERIALS

PIPE TYPE	DN	SOURCES
Ductile cast iron	200 mm	PAM – manufacturer Brødrene Dahl – Duktus pipe supplier
PVC	225 mm	Pipelife – Norwegian manufacturer Wavin – supplier
PE100	250 mm	Pipelife – Norwegian manufacturer Hallingplast – Norwegian manufacturer Wavin – supplier
GRP	200 mm	APS – supplier of Flowtite pipes
Ductile cast iron	600 mm	PAM – manufacturer Brødrene Dahl – Duktus pipe supplier
PE100	710 mm	Pipelife – Norwegian manufacturer (special orders) Hallingplast – Norwegian manufacturer Wavin – supplier
GRP	600 mm	APS – supplier of Flowtite pipes

In cases where the chosen pipe type is available from a number of Norwegian suppliers, information was obtained from at least two of the manufacturers concerned. This study was entirely dependent on the cooperation of suppliers/manufacturers, and constructive meetings and follow-up were crucial in enabling the analysis to be carried out.

The aim of the analyses was to compare different pipe materials, rather than differences between the manufacturing processes used for pipes made from the same material. In cases where a number of suppliers provided figures concerning the same pipe type and their associated manufacturing process and raw material composition, an assessment was made as to which data set was most comprehensive. This data set was then used in the analyses. The data sets were also subject to checks to ensure that they were not significantly non-conformant.

Some of the values concerning raw materials and activities upstream of the pipe manufacture were obtained directly from Ecoinvent, SimaPro's database. In some cases, information on the manufacturing of pipes was obtained from previous life cycle analyses. This was done in order to save time, as the process of obtaining information and mapping is both wide-ranging and time-intensive.

4.2 STRUCTURE OF THE ANALYSES

A major challenge associated with conducting an LCA analysis is to maintain objectivity throughout the entire process. A number of studies have noted that many LCA analyses have resulted in conclusions in favour of the client, the product being compared or assumptions that were adopted in advance of the analysis (Karlsson et al. 2007; Standard Norge 2006a). Such conclusions can weaken the general perception of an LCA analysis' credibility. Based on this, it is very important to chose system boundaries carefully and to be conscious of the assumptions that are adopted in advance. The analyses in this study were carried out with the aim of determining whether some of the pipe materials point in a positive or negative direction with regard to different environmental loads. An objective approach without either preconceptions or specific hopes as regards the outcome of the analysis was adopted insofar as is possible. Experiences from the literature study were also utilised in connection with the formulation of the analyses.

FUNCTIONAL UNIT

In this study, functional unit is defined as *100 metres of pipe (of a specific material and with a specific dimension) delivered to the construction site*. The four pipe materials ductile cast iron, GRP, PE and PVC were all analysed for internal diameter as close to 200mm and 600mm as possible, with the exception of PVC, which is not manufactured in the latter dimension.

SCOPE

The LCA analyses consider the life cycle of the respective pipes through to the installation phase. This entails environmental impacts associated with raw material refining, pipe manufacture and transportation stages through to the arrival of the pipes at the construction/installation site. This would appear to be a reasonable decision, as the analysis results are intended for use as a basis for decision-making with regard to pipe material selection in connection with project engineering.

Thus, the life cycles considered in the analyses do not cover activities relating to pipe-laying, the use phase or the handling of the pipes at the end of their useful life. However, these life cycle phases are described in a later section, on the basis that they have been omitted from the analyses.

SYSTEM BOUNDARIES

It was decided to consider the life cycle of each of the pipe materials fairly schematically, as shown in Figure 4.1. For each of the phases, material and energy flows were chosen wherever possible so that any differences between the various pipe materials will be apparent, without encompassing such a broad range that the analyses will be difficult to carry out due to inadequate or insufficient underlying data.

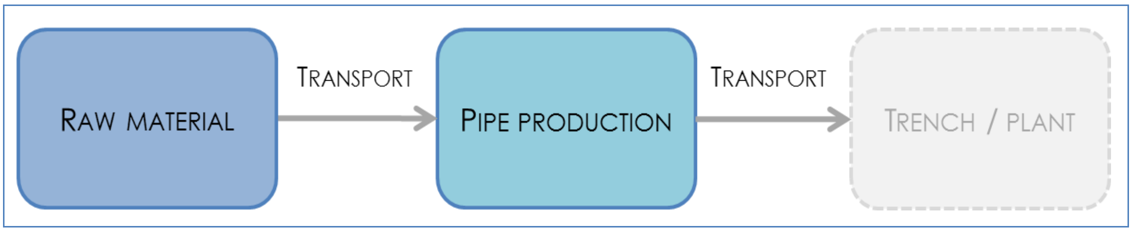


FIGURE 4.1 – SIMPLIFIED ILLUSTRATION OF THE PIPES' LIFE CYCLE

Raw material

Information on the various raw materials used in pipe manufacture was obtained from Ecoinvent, SimaPro's database, and is not site-specific. This was done because the pipes that are supplied to Norway are manufactured by various factories around Europe which obtain their raw materials from a variety of sources. Using site-specific data for a particular factory would therefore have given an inaccurate result. The raw materials used in the manufacture of pipes have already been refined through various processes (depending on the type of raw material concerned) before it arrives at the pipe factory. All the background processes linked to a raw material form part of the life cycle of the raw material and become part of the total life cycle of the pipe material that is analysed. This means that the raw materials contribute material and energy consumption linked to these processes, as well as emissions from any transportation stages involved in their life cycle. The information on the background processes are largely based on regional or global mean data.

Pipe manufacture (energy consumption)

This life cycle phase only encompasses energy consumption, as all raw materials used in the manufacturing process are considered as a separate phase, as described in the previous section. In the pipe manufacturing process, site-specific data was used as a basis insofar as was possible. Any non-conformities are described in Chapter 5 under the life cycle description for the pipe material concerned. Factory maintenance is considered at a general level only and solely as part of the factory's overall energy consumption. The replacement of production equipment and other material flows in connection with daily operation and maintenance has been excluded.

It was decided not to consider the manufacture of any joints and other pipe components linked to 100m pipe sections. This decision was taken in order to simplify data acquisition, which is generally very time-intensive. Remarks are presented on requirements concerning the storage and packaging of finished pipes, but not included in the analyses.

Wholesaler/supplier

Some of the pipes are delivered directly from the factory to the installation site, but it is not unusual for standard pipes to be stored by a wholesaler in order to offer short delivery times. Estimating a percentage share for pipes which are temporarily stored in this way was not easy, and this step was therefore omitted from the final analysis.

Trench/installation

This phase was not included in the analyses, as the background information was deficient. It is noted that some recent studies have found that stresses caused during the installation phase are insignificant and also fairly consistent between the various pipe materials (see the literature study). Nevertheless, a number of factors can play a role in this regard, although they have not been included in the analyses. The pipes are stored as specified by the manufacturer, e.g. on the requisite surface and with any necessary packaging around the pipes. Some remarks on the materials are presented here. Remarks are also presented on the proportion of cut pipes and damaged pipes which are not used and the way in which these were treated afterwards in cases where information was available.

Transportation

All data regarding transportation was obtained from the relevant pipe manufacturers and suppliers and are therefore site-specific for a particular factory. It was decided to use this information in order to obtain real input data, although it could be argued that it weakens the generality in the analysis results. This is discussed in the sensitivity analyses.

As is apparent from Figure 4.1 on the previous page, two transportation stages were included in the analyses. The first stage is the transportation of the raw materials to the pipe factory. Here, some distances and transportation modes were estimated/assumed by the supplier based on the fact that raw material extraction can take place on all continents. The next transportation stage, that from the factory directly to the installation site, is well-documented by suppliers. The transportation modes used include ship, road, fork-lift truck and rail. The loading, unloading and transhipment of pipes, with the lifting appliances that are associated with these operations, was not included. More details of the transportation phase can be found under the respective life cycle descriptions and in Appendix C.

All distances were calculated using the Norwegian Yellow Pages' map service (gulesider.no 2012). The transportation stage from factory to installation site was calculated through to Oslo in all cases.. It was also documented by the respective sources that all the pipe types are transported in the same way, regardless of whether they are delivered to Eastern Norway or elsewhere in Norway.

Operation and maintenance during the use phase of the pipes

This life cycle phase is not included in the analyses, as it is difficult to obtain adequate information. Maintenance and repair requirements are poorly documented, and the information that is available is not considered to be sufficiently relevant. This is because repairs are often due to inappropriate handling of pipes during laying or the wrong choice of pipe and pipe coating from the start. The validity of the analysis results therefore presupposes the correct handling of pipes in all phases.

Nevertheless, it is noted that stresses arising during the pipes' use phase can be important as regards the total life cycle inventory, particularly if the daily operation of the pipe network in which the pipes are used involves pumping (see the literature study).

Life-expiry

Based on today's technology and knowledge concerning both pipe materials and pipe network operation, it is considered reasonable to assume that the pipes will have a useful life of 100 years. This is also a requirement for the pipes that are manufactured and applies to all pipe materials and dimensions (VA/Miljø-blad 2001; VA/Miljø-blad 2003; VA/Miljø-blad 2007a; VA/Miljø-blad 2007b). Accordingly, it was decided to ignore any handling of used pipes, because it is very uncertain how this will actually be carried out when the time comes. There is currently no standard Norwegian practice for handling pipes as waste at the end of their useful life. The pipes are usually left in the ground after they have been decommissioned. In the case of the insertion of liners into pipes, the existing pipes are sectioned and envelope the new pipes which are drawn into the existing pipe. If a pipe section is relaid, the pipes will remain in-situ without further handling.

ENERGY MIX

Energy, in this case in the form of electricity, varies both geographically and with time. As described in the literature study, the type of electricity source that is used can have a substantial impact on the outcome of a life cycle analysis. It was decided to use a common European electricity mix for the respective manufacturing processes covered by the analyses, regardless of the country in which the pipes are manufactured. This was done to avoid favouring one country of manufacture (and one manufacturer) over another. The chosen mix was based on generation figures from 24 European countries which are members of ENTSO-E (European network of transmission system operators for electricity), formerly the UCTE (Union for the Coordination of the Transmission of Electricity). The figures date from 2000

WEIGHTING IN CONNECTION WITH CONVERSION

All input data in the analyses were converted to values which can be directly related to a metre of pipe made from the material concerned. This means that assessments were made of what proportion of production the analysed pipe section of one metre amounts to, as a fraction of total production by weight. Most values in connection with the factories were specified in tonnes/year and then converted to the proportion that one metre of a given pipe material and given dimensions amounts to of the annual production. In connection with the analysis, 100 metres of this pipe material was chosen in order to obtain results which correspond with the functional unit.

4.3 ANALYSIS TOOLS

SIMAPRO

The analysis tool SimaPro was used to conduct the life cycle analyses. Other alternatives were considered, but SimaPro was chosen because it is a recognised and frequently used tool for life cycle analyses which has been available on the market for many years. SimaPro was developed by PRé Consultants in the Netherlands, and is a comprehensive computer tool for calculating life cycle analyses of products and services. The tool enables the acquisition, processing and interpretation of emissions data. The program contains characterisation methods for different regions around the world and is compatible with many inventory databases. The software is continually updated to take account of developments within characterisation methods and databases (Goedkoop et al. 2010).

ECOINVENT

Ecoinvent is a database which is continually developed by the Ecoinvent Centre in Switzerland. The database is the world-leader as regards updated life cycle inventory data, which are both consistent and transparent. The database contains more than 4,000 data sets with life cycle inventories within agriculture, energy supply, transportation, biofuel, chemicals, construction materials, packaging, metal refining and waste management. The database is compatible with most major software programs within LCA and eco-design, including SimaPro (Swiss Centre for Life Cycle Inventories 2012).

4.4 PRESENTATION OF RESULTS

In SimaPro, it is possible to look at a number of types of impact categories using various presentation methods. The impact categories are dependent on the input data, and the presentation method is chosen after the analysis has been built up and all values have been entered. It was decided to look at several types of impact in this study. These are presented in their respective sections. These are recognised analysis criteria and some of them can be compared with findings from previous studies.

RECIPE

ReCiPe is an environmental characterisation method in SimaPro, which is recommended for use in all European life cycle studies (Misa Miljøsystemanalyse 2012). Figure 4.2 shows how different environmental loads contribute to the various environmental classes that are considered, the consequences of these loads and the impact category that the various harmful impacts end up in. In the first instance, 18 environmental indicators were classified into different types of environmental impact, designated *midpoint* in the figure. These impacts were also categorised according to the type of harmful impact that they cause. These harmful impacts ultimately end up in one of the three main categories of environmental impacts. Some of the points from the midpoint will not be categorised further with regard to the type of harmful impact. These are indicated by a red dot in the figure.

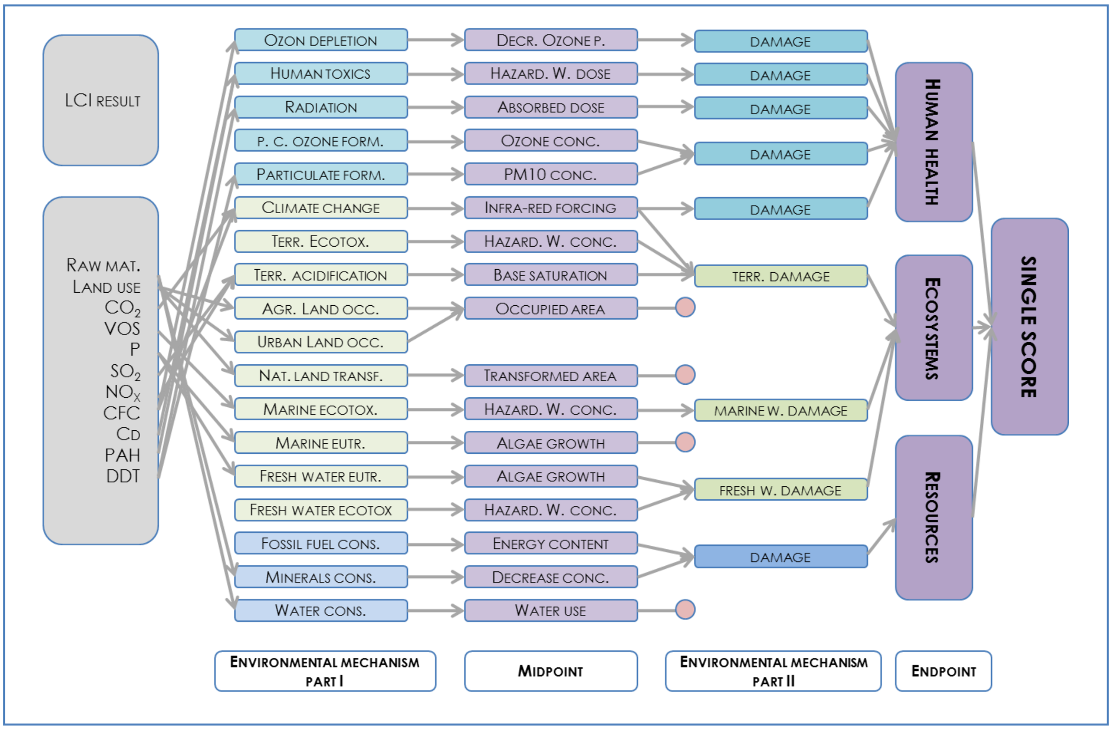


Figure 4.2 – Overview of ReCiPe's impact classification system (after Goedkoop et al. 2012)

The three main categories of environmental impact are described below:

Human health is measured in DALY (disability-adjusted life years), i.e. an indication of the total burden of disease, expressed as the number of years lost due to disease, poor health, disability or premature death. The measurement unit DALY is a function of YLD (years lived with disability) and YLL (years of life lost), i.e. the sum of the number of years lived with a disability and the number of years of life lost. Human toxins, particulate formation and radiation are amongst the environmental indicators which influence this impact category.

Ecosystems is measured in species*years and gives an indication of the risk of different species becoming extinct, either within certain regions or globally. Indicators which influence this category include land use, environmental toxins in terrestrial and aquatic environments and soil acidification. A distinction is made between terrestrial, freshwater and saltwater individuals.

Resource depletion is measured in increased costs (USD). The risk of future generations running out of resources which are being consumed today is often referred to as an important topic. ReCiPe's approach to this impact category is to consider the geographic distribution of minerals and fossil resources, and to assess how the use of such resources entails changes in the work to extract future resources. The recycling of resources and any substitutes is taken into account in the calculations (Goedkoop et al. 2012).

There are various approaches to the handling of uncertainty and assumptions in the characterisation model, and three possible perspectives can be adopted:

- Individualistic (I) which is based on short-term interests, undisputed impact types and optimism as regards the ability of mankind to adapt, as well as the belief that future technological solutions can avoid many potential problems.
- Hierarchical (H) which is based on the most common political principles with regard to time perspective, among other things. This is often considered to be the standard perspective and is the most frequently used perspective in scientific models.
- Egalitarian (E) which takes the most precautions, has the longest time perspective and uses impact types which are not fully established and which therefore only have a selection of indicators available. This perspective is based on the precautionary principle (*Characterisation and Normalisation factors* 2012; Goedkoop et al. 2012).

The analyses in this study use the hierarchical perspective, as this is the most politically accepted perspective and the most often used in scientific models. It appears to be an intermediate position between the other two perspectives with regard to both time perspective and the scope of the assessments involved.

A distinction is made in ReCiPe between midpoint and endpoint analyses, i.e. how far the various environmental indicators are aggregated (as shown in Figure 4.2). Midpoint analyses give results for all 18 environmental indicators used in the classification, whereas endpoint analyses give three results, one for each of the impact categories.

In this study, endpoint analyses were used to present the results for the three main categories: human health, ecosystems and resource depletion. The results are also presented as a single value for each of the pipe materials, known as a *single score*. This value consists of three interim sums, one from each of the impact categories, and represents an overall assessment of all aspects. The interim sums are weighted and normalised so that the single score value has no denomination A lower value indicates that fewer environmentally harmful emissions and negative impacts are associated with the pipe material.

From the midpoint analyses, the results for three selected environmental indicators are presented. These are described in more detail in the following sections:

Climate change [kg CO_2 equivalents]

The environmental indicator which is referred to as *climate change* in ReCiPe is often called global warming potential (GWP). Anthropogenic emissions of greenhouse gases contribute to anthropogenic greenhouse effects. The greenhouse effect is defined as the effect of the atmosphere limiting the radiation of energy from the earth. The term gives a picture of how the atmosphere retains energy in the form of heat in the same way as a greenhouse. The so-called greenhouse gases include water vapour, carbon dioxide, nitrous oxide, ozone, methane and chlorofluorocarbons. The indicator for the thermal activity of a gas, i.e. the effect of each of these gases on global warming, is specified relative to CO_2, which is set to 1. Anthropogenic emissions of greenhouse gases result in increased atmospheric concentrations of these gases. This can potentially contribute to higher temperatures, polar ice cap melting, sea level rise and regional climate changes. In the hierarchical perspective in ReCiPe, the time frame for climate change is set to a hundred years. Figure 4.3 illustrates how this indicator is classified. As the figure shows, climate change impacts on both human health and ecosystems.

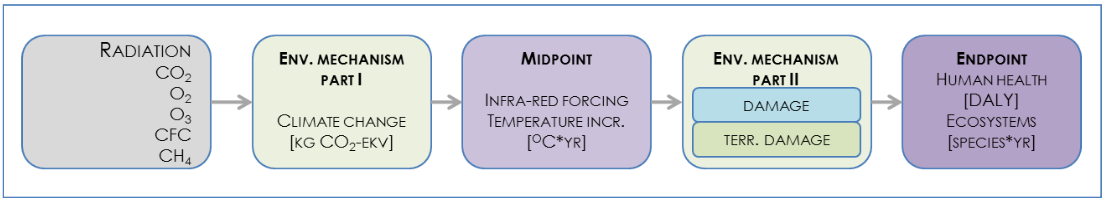


FIGURE 4.3 – THE INDICATOR 'CLIMATE CHANGE' IN RECIPE'S ENVIRONMENTAL CATEGORISATION SYSTEM (AFTER GOEDKOOP ET AL. 2012)

Fossil fuel consumption [kg oil equivalents]

The term 'fossil fuel' covers hydrocarbons such as methane, liquid petroleum and coal. A distinction is made between conventional fossil energy sources such as these, and unconventional fossil energy sources such as extra heavy oil, oil sand and oil shales. Unconventional energy sources are often more expensive to refine, and the consumption of conventional fuels therefore contributes to increased costs in two ways: in the form of higher prices due to strong demand, and increased costs associated with the extraction of unconventional energy sources. In this impact class, it is the consumption of conventional energy sources and the way in which this impacts on demand for the extraction of unconventional energy sources which forms the basis for calculation of the impact. The characterisation factor is based on the projected change in the supply ratio between conventional and unconventional energy sources. The hierarchical perspective utilises a time perspective of around 100 years at current production rates, and looks at the marginal cost increase after 3000 billion barrels of oil have been extracted. Figure 4.4 illustrates how this environmental indicator is classified in ReCiPe.

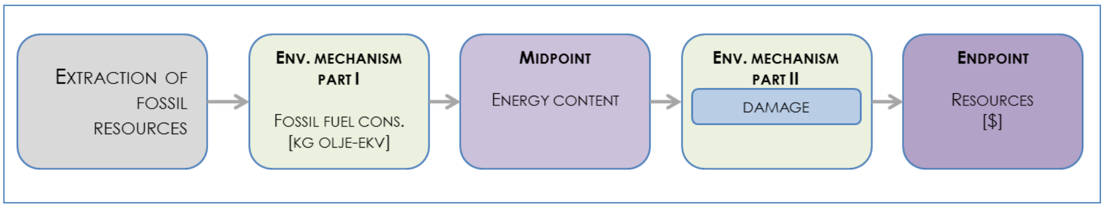


Figure 4.4 – Fossil fuel consumption in ReCiPe's environmental categorisation system (after Goedkoop et al. 2012)

Mineral depletion [kg Fe equivalents]

Mineral resource consumption is calculated on the basis of the quantity of minerals that are extracted. The principal data source used to calculate mineral depletion is a database from the United States Geological Survey, which contains historical data concerning mineral extraction from over 3000 mines. The extent of harmful effects is defined as the net added costs (calculated on a present value basis) which society must pay as a result of an extraction. The calculation method is the same for all three perspectives (Goedkoop et al. 2012). Figure 4.5 illustrates the environmental indicator 'mineral depletion' in ReCiPe's classification system.

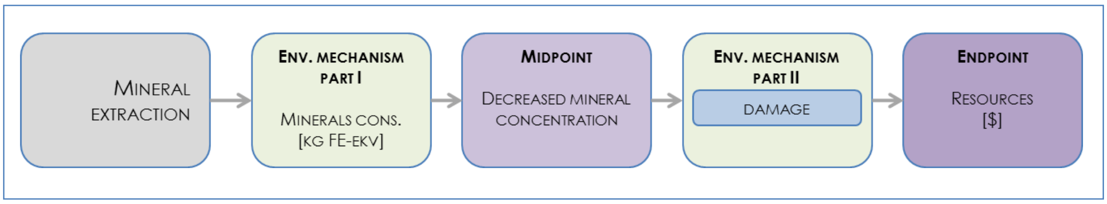


Figure 4.5 – The indicator 'mineral depletion' in ReCiPe's environmental categorisation system (after Goedkoop et al. 2012)

ECO-INDICATOR 99

Eco-indicator is a method which can be used in SimaPro to assess the total environmental load associated with a product or service. The environmental concept is three-fold and encompasses human health, ecosystems and resource depletion. The ReCiPe analysis method is based on this method (Goedkoop & Spriensa 2000).

Eco-indicator 99 produces results in the form of single score values, based on one of three perspectives (I/H/E), corresponding to the perspectives previously described for ReCiPe.

In order to obtain consistent results, the hierarchical perspective is also used in these analyses. Table 4.2 illustrates how the three impact categories are weighted in this perspective in Eco-Indicator. Figure 4.4 shows which environmental indicators are included in the assessment and how they are weighted in relation to each other.

TABLE 4.2 – ECO-INDICATOR'S WEIGHTING OF THE IMPACT CATEGORIES IN THE HIERARCHICAL PERSPECTIVE

	HUMAN HEALTH	ECOSYSTEMS	RESOURCE DEPLETION
Weighting [%]	40	40	20

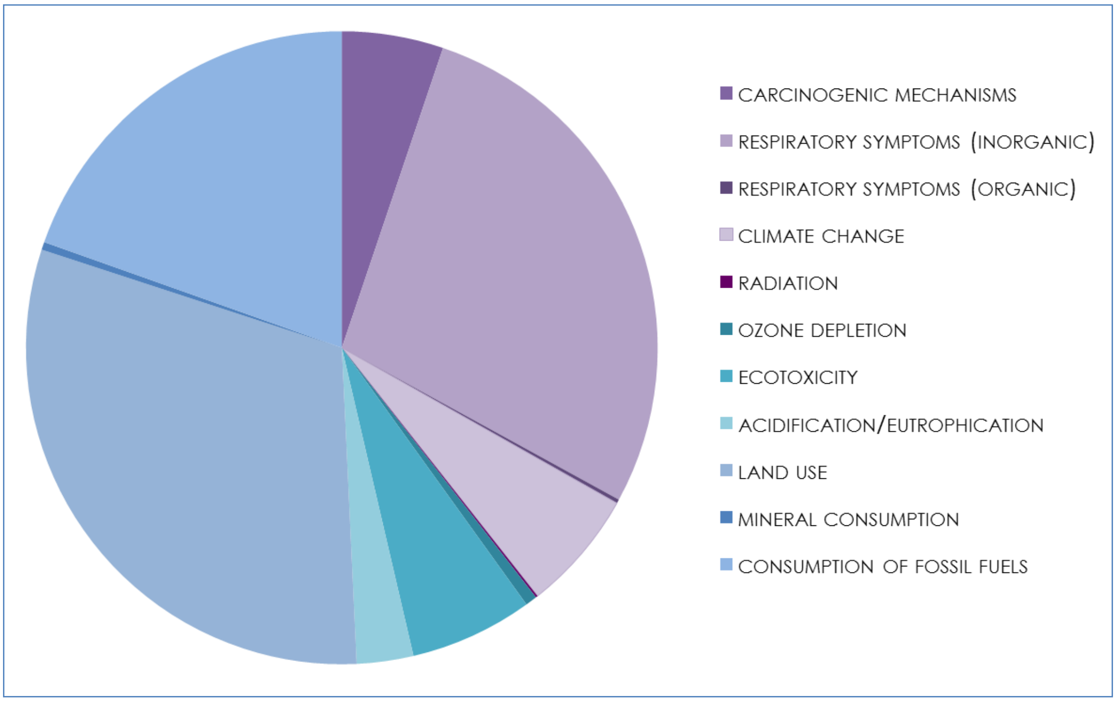


FIGURE 4.6 – WEIGHTING OF ENVIRONMENTAL INDICATORS IN ECO-INDICATOR 99

5 LIFE CYCLE DESCRIPTIONS

The analyses for each of the pipes follows the same layout, but use different input data for raw materials and energy sources in the manufacturing process, as well as different transportation modes and transportation distances. The life cycle for each of the pipes which were analysed is therefore repeated in the following sections, with an overview of all the elements included and selected input data. Unless stated otherwise, information was obtained from the relevant pipe manufacturers and suppliers following meetings. Supplementary information in the analyses was estimated on the basis of historical data concerning processes or material use; this is accounted for.

5.1 DUCTILE CAST IRON

Ductile cast iron pipes primarily consist of iron, both pig iron and scrap iron. The scrap iron is bought on the international scrap iron market. The origin of the raw material used in pipe manufacture is therefore extremely variable, and it is difficult to determine by what mode and how far it has been transported before it arrives at the factory. The iron ore that is used originates from mines in South America, Asia, Australia and to some extent from Europe. It is delivered to factories in Europe, primarily by ship to the continent, before being forwarded by road and rail. Coke is also used in the manufacturing process. This is delivered by ship from either Svalbard or Australia.

Around 2-3% of pipes are rejected during manufacture. The scrap iron from these pipes is used in production again, while the cement component is recycled as fill material. Pipes which are rejected after pressure testing only have weaknesses at the 'sharp end'. These pipes are cut 10-15cm in from the end and can then still be used. The finished pipes are stored sleeve end to sharp end. Plastic or wood chip is placed between the pipes to prevent damage to their exteriors. Both pipe ends are packaged with a plastic plug made from PE of satisfactory hygienic quality.

The pipes are transported by road to Norway, via ferry from Denmark to Larvik or another port along the east coast of Norway. Around 20 tonnes of pipes are carried by each heavy goods vehicle and the pipes have to be loaded and unloaded using rubberised hooks/forks operated from an excavator, fork-lift truck or vehicle. Little damage occurs during transportation, and primarily only cosmetic scratches occur on the surface of the pipes, which can be repaired upon arrival. This is done by applying an epoxy paint or another coating. However, pipes that fall off cannot be used and must be transported to a scrap dealer. Some pipes are transported to wholesalers in Norway, who then store them and deliver them upon request. The pipes are then transported by road from the wholesaler. Large deliveries of pipes take place directly from the factory to construction sites in order to minimise unloading.

DN 200

The pipes have an internal diameter of 201mm. One heavy goods vehicle (HGV) is capable of transporting 20 tonnes of pipes, which corresponds to 538 metres of pipe or 90 pipe lengths. All pipes up to a diameter of 350mm are delivered in bundles with a diminishing number of pipes as the diameter increases. Bundles of six DN 200 pipes are lashed together using steel or plastic straps. The pipes are stored on wooden trestles up to a maximum of 10 rows high. Pipes of this dimension weigh 37kg/metre.

DN 600

These pipes have an internal diameter of 605mm. One HGV can transport 118 metres of pipe of this dimension (20 pipe lengths). The pipes are stacked up to four high, separated by square section timber. The pipes weigh 168kg/metre, which is 4.5 times as much as the DN 200 pipes.

ANALYSIS

The input data relating to the raw material composition of cast iron pipes were obtained directly from an analysis of the molten mass used in production. An approximation of the exact composition has been used in SimaPro, but the precise values are confidential. An overview of the main components of the pipes is presented in Table 5.1:

TABLE 5.1 – DISTRIBUTION OF RAW MATERIALS IN DUCTILE CAST IRON PIPES

RAW MATERIAL	QUANTITY (PERCENTAGE BY WEIGHT)
Iron (pig iron/scrap iron)	93%
Coke (graphite)	4%
Other additives (Mg, Mn, Si +++)	3%

The ratio between pig iron and scrap iron varies according to availability and price on the international market, and from factory to factory. The proportion of scrap iron was estimated as being 90% by both suppliers used as sources in this study, while other estimates varied between a minimum of 50% and a maximum of 90%. The ratio between pig iron and scrap iron can play an important role in the life cycle inventory, and a separate analysis with a higher proportion of pig iron was conducted to see how this changes the overall picture for ductile cast iron pipe.

The consumption of energy in the form of electricity and gas has been specified as the factory's total annual costs for the production of 90,000 tonnes of pipe: EUR 5.8 million. It was not possible to obtain more specific data from the suppliers used as sources in this study. The energy consumption of the pipes was therefore estimated based on data for the steel industry, combined with data relating to location-specific electricity and gas prices.

Electricity supplied to industry (Germany): EUR 102,400 per GWh (*Electricity Industry* 2012)

Natural gas supplied to industry (Germany): EUR 46,200 per GWh (*Natural Gas Industry* 2012)

The information in Table 5.2 was obtained and converted from the Energy Consumption table (U.S EIA 2010), and shows the total consumption of electricity and gas in the American iron and steel industry for three years:

TABLE 5.2 – CONSUMPTION OF ELECTRICITY AND GAS BY THE IRON AND STEEL INDUSTRY (AFTER US EIA 2010)

ENERGY FORM/YEAR	2007	2008	2009
X = Electricity [GWH]	60,146	53,592	18,705
Y = Gas [GWH]	124,091	115,884	54,491
Ratio (X:Y)	1:2.06	1:2.16	1:2.91

The mean ratio between X and Y for these three years is 2.38. This gives the following equation for the cost contribution from X and Y for electricity and gas respectively:

$102{,}400\ X + 46{,}200\ Y = 5{,}800{,}000$

$102{,}400\ X + 46{,}200 * (2.38\ X) = 5{,}800{,}000$

$X = 27.3$ GWh

$Y = 65.0$ GWh

Broken down into an annual production of 90,000 tonnes of pipes, this gives an electricity consumption of 0.30kWh/kg of pipe and a gas consumption of 0.72kWh/kg of pipe. These values were used for energy consumption in the life cycle analyses for ductile cast iron pipes.

The place of origin of the raw materials and transportation to the factory were estimated by the supplier in consultation with the factory. The transportation of the finished pipes is documented by the supplier with regard to both the mode of transportation used and the distances involved. A schematic representation of the life cycle for ductile cast iron pipe as analysed in SimaPro is presented in Figure 5.1:

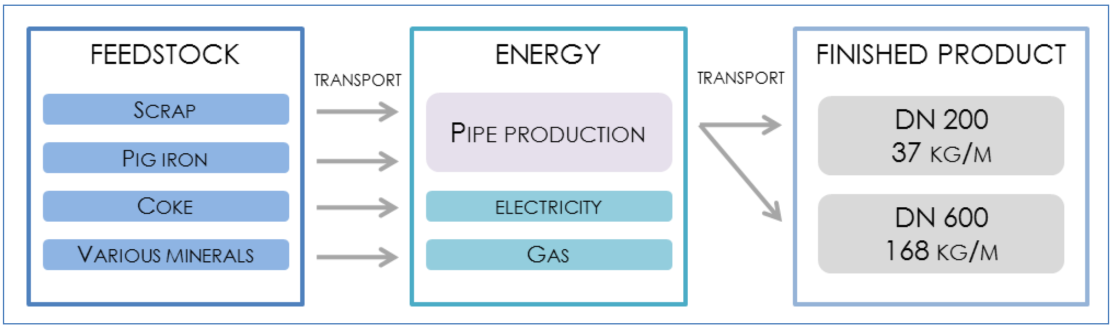


Figure 5.1 – Schematic representation of the life cycle of the ductile cast iron pipes analysed

5.2 Glass fibre reinforced polyester (GRP)

GRP pipes were previously manufactured in Norway, but are now supplied by factories in Europe. The majority of the deliveries to Norway originate from a factory in Gdansk in Poland. The raw materials used are available from innumerable sources, provided that they satisfy the quality requirements determined by the pipe manufacturers.

DN 200

This pipe dimension, which has an internal diameter of 208.9mm, is uncommon in Norway, as GRP pipe is largely used in diameters of 500mm and upwards due to economic competitiveness in this segment. GRP pipes in the dimension span 100-300mm are only produced in Germany in a discontinuous process in six-metre pipe lengths. The pipes are then transported by road from Germany to their destination in Norway. A total of 768 metres of pipe (127 pipe lengths) of this dimension can be transported by one HGV. The pipes weigh 6.8kg/metre.

DN 600

GRP pipes of this dimension (internal diameter of 604mm) are supplied in lengths of 12 metres from the factory, and are transported by road to construction sites in Norway. One HGV can transport 192 metres of pipe (16 pipe lengths) of the dimensions concerned. These pipes weigh 30.6kg/metre, about 4.5 times as much as pipes with a nominal diameter of 200mm.

Analysis

The raw material composition of the pipes was specified by Flowtite Technology AS (Hausberg 2012). The composition varies according to the diameter, and the quantity of glass fibres increases considerably with increasing pipe diameter. The distribution of raw materials for DN 200 and DN 600 is presented in Table 5.3.

TABLE 5.3 – DISTRIBUTION OF RAW MATERIALS IN GRP PIPES

	QUANTITY (KG PER METRE OF PIPE)	
RAW MATERIAL	DN 200	DN 600
Polyester-resin	2.3	8.5
Glass fibre	1.9	12.1
Quartz sand	2.6	10.0

The input data relating to energy consumption were obtained from a comprehensive LCA analysis (Ressourcen Management Agentur GmbH 2011) of Flowtite's GRP pipe. The analysis covers Flowtite's pipe production in Spain. The majority of the production data in this analysis dates from 2009. The energy consumption was calculated based on the factory's total consumption of electricity and gas and the total annual pipe production:

Total production, GRP pipes:	22,431 tonnes		
Electricity consumption:	3,365,245kWh	=	0.15kWh/kg of pipe
Liquefied petroleum gas (LPG):	185,714 litres	=	0.054 litres/kg of pipe

The transportation of raw materials to the factory in Spain was carefully documented by the manufacturer. The mode of transportation used and the distances for the transportation of finished pipes were specified by the supplier. Figure 5.4 presents a simplified version of the life cycle of GRP pipes.

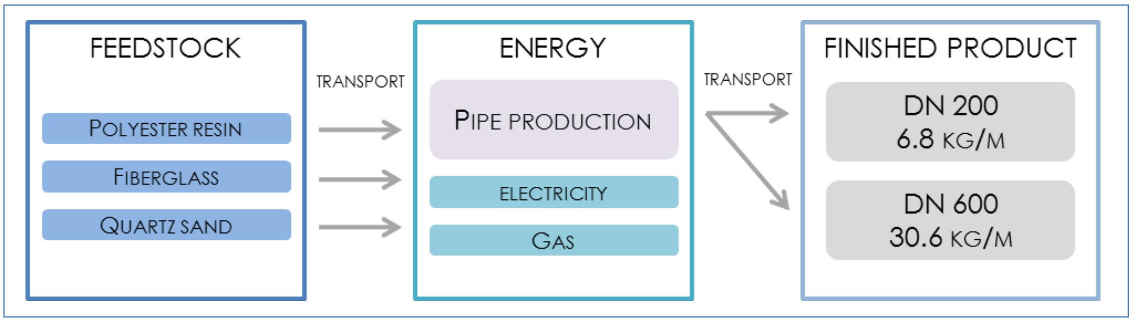


FIGURE 5.2 – SCHEMATIC REPRESENTATION OF THE LIFE CYCLE OF THE GRP PIPES ANALYSED

5.3 POLYETHYLENE (PE)

PE pipes are primarily supplied to the Norwegian market from factories in Norway and elsewhere in Scandinavia. The raw material used in the manufacturing process is PE granules supplied by Borealis. Material discarded during the manufacturing phase is re-added to the melt and is used for new pipe production. An upper limit is used for the regranulate content of each individual pipe; however, all materials that are discarded in the factory are reused on site. Most discarded pipes originate from the transition between pipe series of different colours; here, 30-40 metres of colour-graded pipe with no clear colour identity is being produced, so this length must be remelted.

Finished pipes are stored outdoors, under a metal roof or tarpaulin. The pipes are bound using a wooden framework and steel banding every three metres during transportation. In cases where a delivery is large enough to fill an HGV, the pipes are supplied directly from the factory to the construction site. In other cases, the pipes are transported via a wholesaler located centrally in Eastern Norway. Transportation is primarily carried out by HGV, and the pipes come in straight lengths of 6 or 12 metres. One exception is pipes that are produced at Pipelife's factory in Stathelle, where pipes can be produced directly in the water and delivered via a marine pipe flotilla in lengths of up to 550 metres.

Upon delivery to the construction site, lifting tools are used to lift the pipe bundles off the vehicle. It is also possible to handle smaller dimensions without using lifting tools, particularly those with a length of 6 metres. A lifting crane is used for larger/longer pipes. Pipe caps are reused on construction sites wherever possible, and there are often only small pipe stumps left over that are not used. These are disposed off by the contractor, and are often taken to incineration plants. In such cases, the plastic is used as an alternative to fuel oil, as it has a high calorific value. New pipes damaged during transportation and pipes that are bleached by the sun as a result of being stored outdoors can be remelted and used to manufacture new pipes, provided that they have not been contaminated by pollutants other than those found in the atmosphere. In other cases, used pipes may be reused in other plastic products with less demanding strength and hygiene requirements. One of the reasons that pipes of unknown origin are not used in new pipe production is that there are stringent hygiene requirements for materials which come into contact with drinking water. This includes the risk of lead being present in old pipes.

DN 250

Pipes of this dimension are stored with a PE plug in both ends without any further packaging. The pipes analysed have an SDR value of 11, which corresponds to a nominal pressure of 16 bar. These pipes have an internal diameter of 204.6mm and weigh 16.9kg/metre.

DN 710

These pipes are relatively thick-walled and have an internal pipe diameter of 581mm. The pipes are stored outdoors on wooden pallets with PE plugs in both ends. The pipes of this dimension were also analysed as having an SDR value of 11, and weigh 112kg/metre, which is 6.6 times as much as the DN 250 pipes.

ANALYSIS

The input data regarding raw materials were obtained from the plastics manufacturer Borealis, which supplies PE granules directly to pipe factories. The following data regarding the PE 100 material were specified and included in the life cycle analysis of the PE pipes:

TABLE 5.4 – DISTRIBUTION OF RAW MATERIALS IN A PE PIPE

RAW MATERIAL	QUANTITY (PERCENTAGE BY WEIGHT)
HDPE (High Density Polyethylene)	> 95%
Black Carbon	approximately 2.5%
Antioxidant (unspecified)	'small proportion'

The confidential ingredient (antioxidant) was omitted from the analysis, as it proved difficult to determine a good approximation for an unknown material in an unknown quantity. It is assumed that what is described as a 'small proportion' will have little effect on the overall impact.

The energy consumption was specified as 0.6kWh/kg of pipe. This value was used directly in the analyses in SimaPro.

Information regarding the transportation of PE granulate to the factory was obtained from the pipe manufacturer. The mode of transportation used and the distances involved in delivering finished pipes were also documented by the pipe manufacturer. A schematic representation of the life cycle of PE pipe is shown in Figure 5.3.

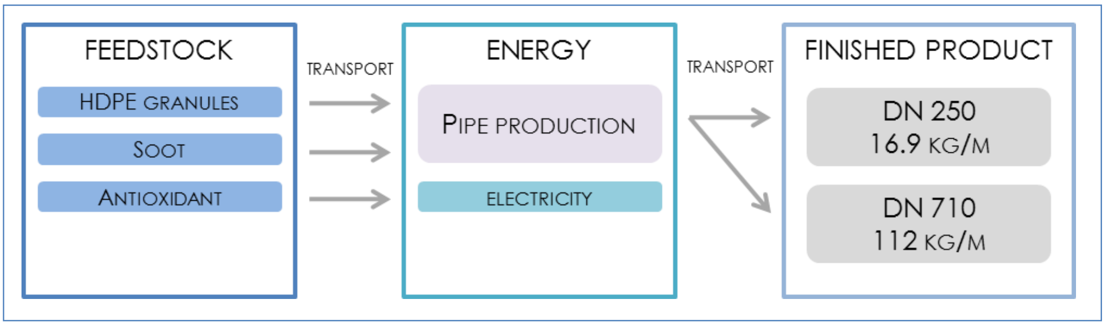


Figure 5.3 – Schematic representation of the life cycle of the PE pipes analysed

5.4 Polyvinyl chloride (PVC)

PVC pipes available on the Norwegian market are primarily produced in Norway and Denmark within the dimension range 63-400mm. The factory in Denmark uses PVC manufactured in Norway and the Netherlands in approximately equal quantities. The plastic is first transported by ship, and then by road to the Danish mainland. Finished pipes are transported by road, possibly by ferry from Denmark. Wherever possible, the pipes are delivered directly to the construction site, although frequently used pipe dimensions are stored temporarily by a wholesaler to ensure availability and enable fast delivery.

DN 225

The pipes are supplied in lengths of six metres. the pipes are stored outdoors on wooden pallets. The pipes selected for the analysis have an SDR value of 21, and weigh just under 12kg/metre. The internal pipe diameter is 203.5mm.

Analysis

Information regarding raw materials, including composition and quantities was provided by the PVC manufacturer Ineos, which supplies raw materials to the pipe factories used as sources in this study. Table 5.5 shows the composition of raw materials in a PVC pipe:

Table 5.5 – Distribution of raw materials in a PVC pipe

Raw material	Quantity (percentage by weight)
PVC	95.7 – 95.9%
Calcium carbonate	1.9%
OBS (organically based stabiliser)	1.9 – 2.1%
Masterbatch (pigment)	0.3%

The energy consumption is specified as the electricity cost per pipe produced of the type *DN 225 PN 12.5 pressure pipe 6 metres*:

Electricity consumption pipe = DKK 23.16
Electricity consumption mixing facility = DKK 5.50
Total cost = DKK 28.66
DKK 28.66 = EUR 3.84 (as of 19.10.12)

Electricity supplied to industry (Denmark): EUR 0.0982 per kWh (*Electricity Industry* 2012)

An electricity cost of EUR 3.84 per pipe length produced of the given pipe type thus corresponds to 39.1kWh/pipe, or 0.56kWh/kg of pipe. The latter value was used in SimaPro.

Information on the transportation of raw materials and finished pipes, both as regards the mode of transportation used and the distances involved, was documented by the pipe manufacturer. Figure 5.4 shows a schematic representation of the life cycle for PVC pipes.

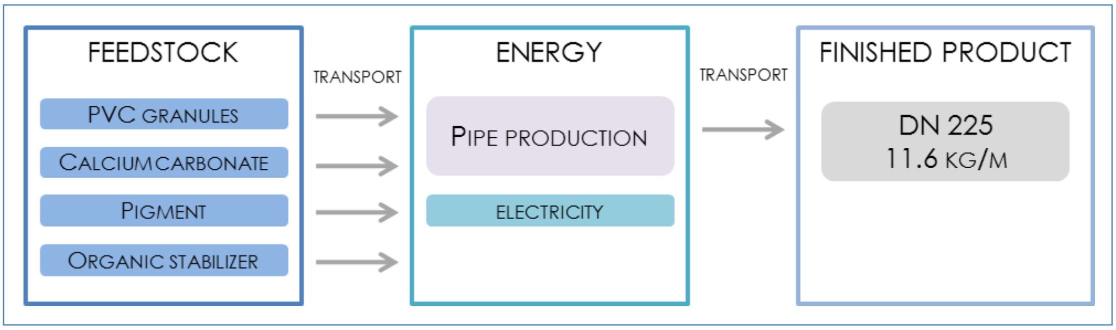


FIGURE 5.4 – SCHEMATIC REPRESENTATION OF THE LIFE CYCLE OF THE PVC PIPE ANALYSED

6 RESULTS

The results of the life cycle analyses performed in SimaPro are presented in this section. All results are presented for the chosen functional unit; a length of pipe of 100 metres delivered to the construction site. The life cycles are divided into the following phases: raw materials, energy consumption and transportation. See section 4.2 for a more detailed explanation of the life cycle phases.

The raw materials, energy and transportation life cycle phases are each indicated by a particular colour; these are **blue**, **turquoise** and **grey** respectively.

It was originally intended that the results for both D_i 200 and D_i 600 would be presented. With the underlying information that is now available, where most of the input data is specified as a number of kg or number of kWh per kg of pipe, the results for the largest pipe diameter are only a scaling-up of the results for D_i 200 for ductile cast iron pipe, GRP pipe and PE pipe. There is therefore little purpose in presenting these in their entirety. Thus, the results below are applicable to pipes with an internal diameter of approximately 200mm. The significance of increasing pipe diameter is considered in section 6.3.

6.1 INDIVIDUAL RESULTS

The results for each of the pipe materials are presented in the subsequent sections. The results were obtained using the presentation method ReCiPe with a hierarchical perspective, which is described in section 4.4. Only the findings from the midpoint analyses are presented for the individual results.

Midpoint

The results for the environmental indicators of climate change, mineral depletion and fossil fuel consumption are presented here. The results show the internal distribution of impact between raw materials, energy and transportation in the life cycles of the pipes.

The tables illustrate the scope of the environmental impacts for each of the pipe materials. The impacts are divided between raw materials, energy consumption and transportation during the life cycles of the pipes.

The figures provide a graphical representation of the distribution of the impacts from the three life cycle phases for all three environmental indicators.

DUCTILE CAST IRON

Midpoint

Table 6.1 presents the contributions from the life cycle phases of raw materials, energy and transportation for the environmental indicators of climate change, mineral depletion and fossil fuel consumption, while Figure 6.1 shows the distribution between the contributions from the three life cycle phases. The distribution is very similar for climate change and fossil fuel consumption, with the largest contribution coming from energy and slightly less coming from transportation and raw materials. However, for the environmental indicator mineral depletion, the contribution from raw materials is completely dominant. This is not surprising given that ductile cast iron primarily consists of iron, which is one of the resources included in the environmental indicator mineral depletion. The contribution from transportation is larger than that from energy for this environmental indicator, although both are considered to be relatively insignificant compared with the contribution percentage from the raw materials life cycle phase.

TABLE 6.1 – CONTRIBUTIONS TO SELECTED ENVIRONMENTAL INDICATORS – DUCTILE CAST IRON

		RAW MATERIAL	ENERGY	TRANSPORTATION
CLIMATE CHANGE	[KG CO_2 EQ.]	1096	1268	1006
MINERAL DEPLETION	[KG FE EQ.]	978	7	43
FOSSIL FUEL CONSUMPTION	[KG OIL EQ.]	369	454	366

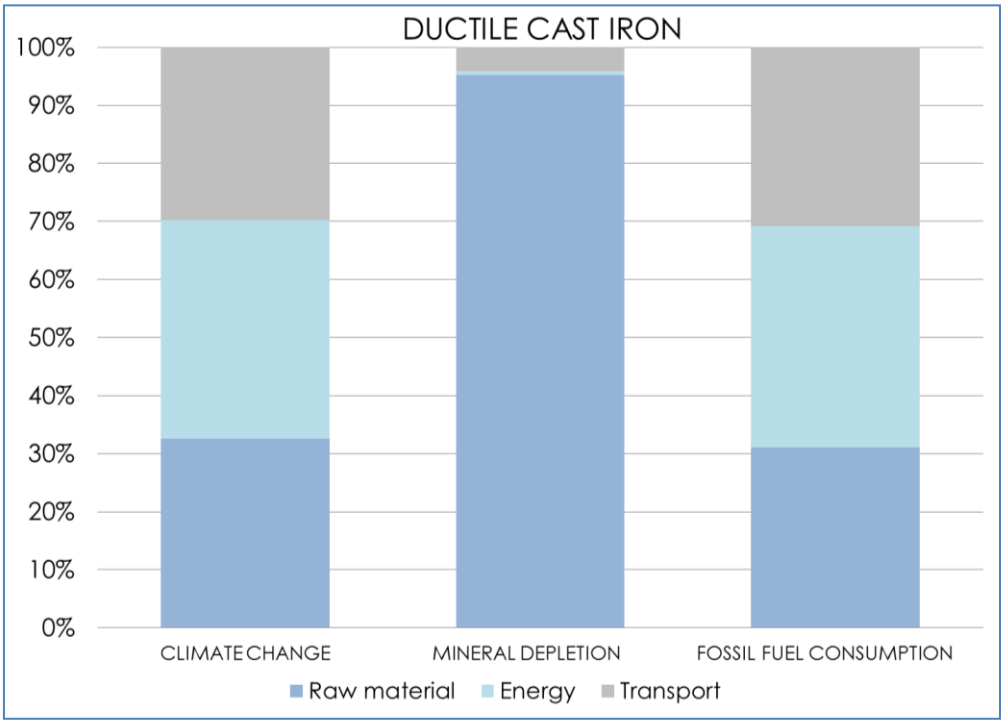


FIGURE 6.1 – DISTRIBUTION OF THE IMPACT OF THE VARIOUS LIFE CYCLE PHASES, MIDPOINT – DUCTILE CAST IRON

GLASS REINFORCED POLYESTER (GRP)

Midpoint

The results from the midpoint analysis for GRP pipe may be studied in Table 6.2. A graphical representation of the contribution distribution between the life cycle phases is presented in Figure 6.2. The relative distribution is fairly systematic, and in all cases the contribution from raw materials accounts for well over 70 percent of the total, while the energy phase is the smallest contributor. A closer look at the analysis results from SimaPro indicates that the various raw materials contribute fairly unevenly to each of the environmental indicators. With regard to climate change and fossil fuel consumption, polyester accounts for the largest percentage, while glass fibre dominates the impact for mineral depletion. Quartz sand has a negligible contribution in all cases, even though this sand accounts for around a third of the weight.

TABLE 6.2 – CONTRIBUTIONS TO SELECTED ENVIRONMENTAL INDICATORS – GRP

		RAW MATERIAL	ENERGY	TRANSPORTATION
CLIMATE CHANGE	[KG CO_2 EQ.]	1278	61	274
MINERAL DEPLETION	[KG FE EQ.]	50	0.4	12
FOSSIL FUEL CONSUMPTION	[KG OIL EQ.]	570	18	100

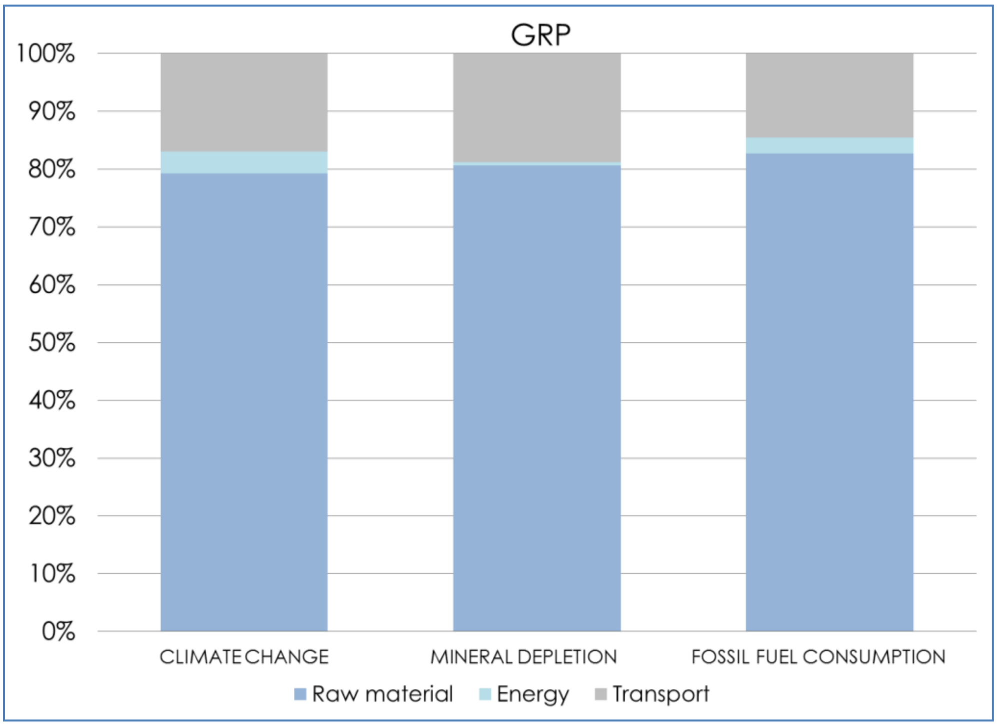


FIGURE 6.2 – DISTRIBUTION OF THE IMPACT OF THE VARIOUS LIFE CYCLE PHASES, MIDPOINT – GRP

POLYETHYLENE (PE)

Midpoint

Table 6.3 and Figure 6.3 show the distribution between the life cycle phases for PE pipe. The distributions of the impact for the environmental indicators of climate change and fossil fuel consumption are somewhat similar in the sense that the majority of the impact originates from the raw materials life cycle phase. However, the contributions from both energy and transportation are around twice as much for climate change as for fossil fuel consumption. For the environmental indicator fossil fuel consumption, the percentage from raw materials is around 90 percent, while it is in excess of 80 percent for climate change. The impacts are most evenly distributed for the environmental indicator mineral depletion; in this case, the raw materials life cycle phase accounts for almost exactly one third, transportation represents around 40% and energy accounts for the remainder. Thus, in this case it is the transportation phase that contributes the most, in contrast to the two other environmental indicators, where the transportation phase contributes the least.

TABLE 6.3 – CONTRIBUTIONS TO SELECTED ENVIRONMENTAL INDICATORS – PE

		RAW MATERIAL	ENERGY	TRANSPORTATION
CLIMATE CHANGE	[KG CO_2 EQ.]	3260	523	143
MINERAL DEPLETION	[KG FE EQ.]	5	4	6
FOSSIL FUEL CONSUMPTION	[KG OIL EQ.]	2879	152	53

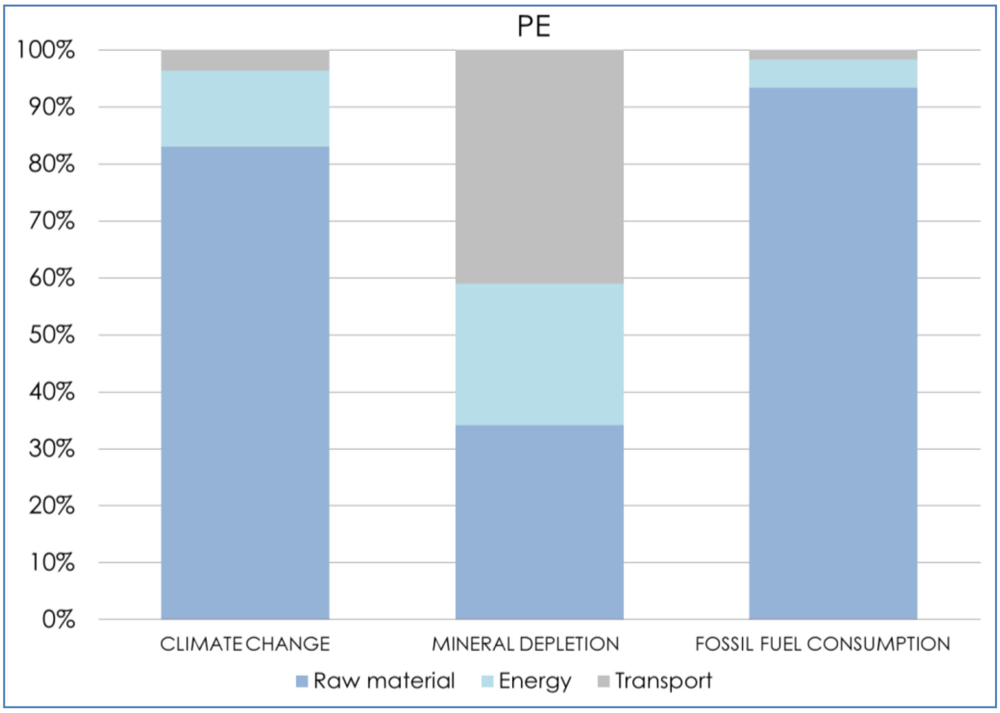


FIGURE 6.3 – DISTRIBUTION OF THE IMPACT OF THE VARIOUS LIFE CYCLE PHASES, MIDPOINT – PE

POLYVINYL CHLORIDE (PVC)

Midpoint

Table 6.4 and Figure 6.4 show the distribution between the life cycle phases of the pipe material PVC. The contribution from the raw materials phase accounts for most of the impact during the life cycle of a PVC pipe. The distribution between the raw materials, energy and transportation life cycle phases is virtually identical for climate change and fossil fuel consumption, with contributions of 91, 5 and 4 percent respectively. The impact for mineral depletion stands out, with the raw materials percentage representing around half, while transportation represents around 35 percent. The energy phase accounts for around 10 percent, i.e. around twice as much as the contribution to the two other environmental indicators. The corresponding figures for PE pipes show a similar pattern, except that the contribution of the energy phase to both climate change and mineral depletion is less for PVC, which in this case has a greater contribution from raw materials.

TABLE 6.4 – CONTRIBUTIONS TO SELECTED ENVIRONMENTAL INDICATORS – PVC

		RAW MATERIAL	ENERGY	TRANSPORTATION
CLIMATE CHANGE	[KG CO_2 EQ.]	5576	318	212
MINERAL DEPLETION	[KG FE EQ.]	14	2	9
FOSSIL FUEL CONSUMPTION	[KG OIL EQ.]	1726	93	77

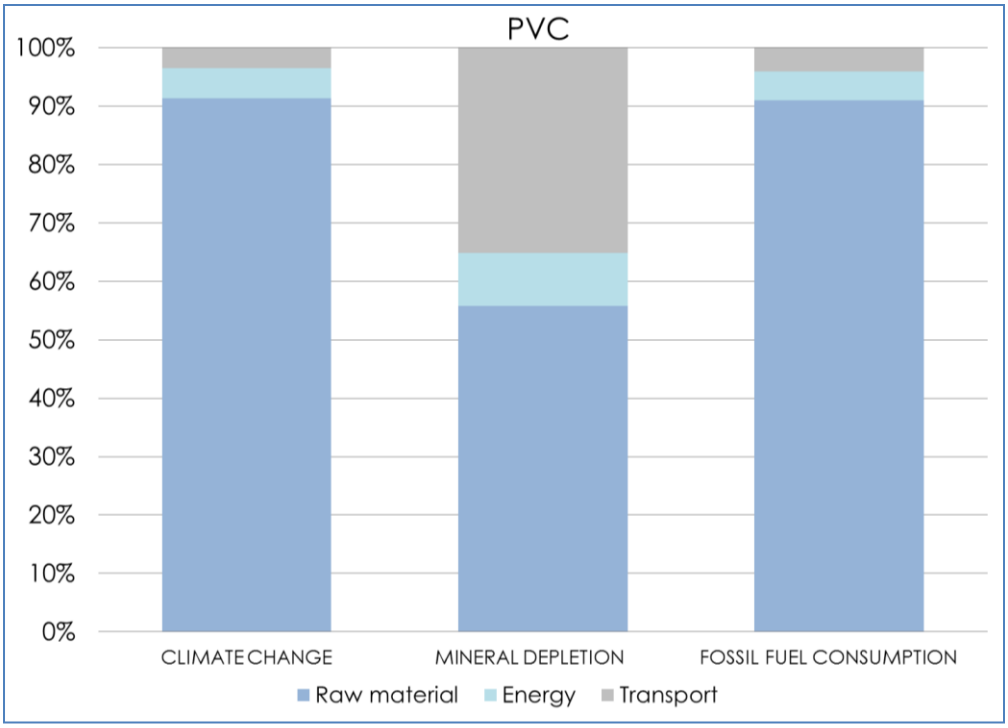


FIGURE 6.4 – DISTRIBUTION OF THE IMPACT OF THE VARIOUS LIFE CYCLE PHASES, MIDPOINT – PVC

6.2 COLLATED RESULTS

The collated results for the four pipe materials analysed are presented in this subsection. The results of the ReCiPe and Eco-Indicator 99 presentation methods are presented here.

From ReCiPe, the results from both the midpoint and endpoint analyses are presented. The intention here is to illustrate the differences between the various raw materials, both broken down between the various phases of the life cycle and overall.

Midpoint
The findings from the midpoint analyses in ReCiPe for the three environmental indicators of climate change, mineral depletion and fossil fuel consumption are presented here. Graphs showing the distribution between contributions from the life cycle phases of raw materials, energy and transportation for the various pipe materials and graphs showing the total impact for the various pipe materials are presented for the three environmental indicators.

Endpoint
The total impact that the pipes have for the three environmental categories of human health, ecosystems and resource depletion is presented here. The figures show both the distribution of the impacts from each of the life cycle phases and the total impact of each pipe.

Single score
Finally, the single score values for each of the pipe materials from both ReCiPe and Eco-Indicator 99 are presented. The results are presented in the form of graphs showing the single score values for all the pipe materials. In both cases, the values consist of subtotals from the environmental categories of human health, ecosystems and resource depletion.

Note that all the results are given for the functional unit of each of the pipe materials; 100 metres of pipe with D_i 200mm delivered to the construction site.

RECIPE MIDPOINT

Climate change

Figure 6.5 shows the impacts of the various pipe materials on the environmental indicator *climate change*. The raw materials life cycle phase contributes the higher percentage of the impacts for the plastic-based materials PE and PVC. PVC stands out as having by far the largest contribution, both for raw materials and overall. Ductile cast iron accounts for the smallest contribution for the raw materials life cycle phase, while the impacts from both the energy and transportation phases are greater than the contributions from the three other pipe materials combined. GRP pipe stands out in a positive way with a contribution of less than 2,000kg CO_2-equivalents, which is around half of the emissions associated with ductile cast iron pipe, which represents the next smallest total contribution.

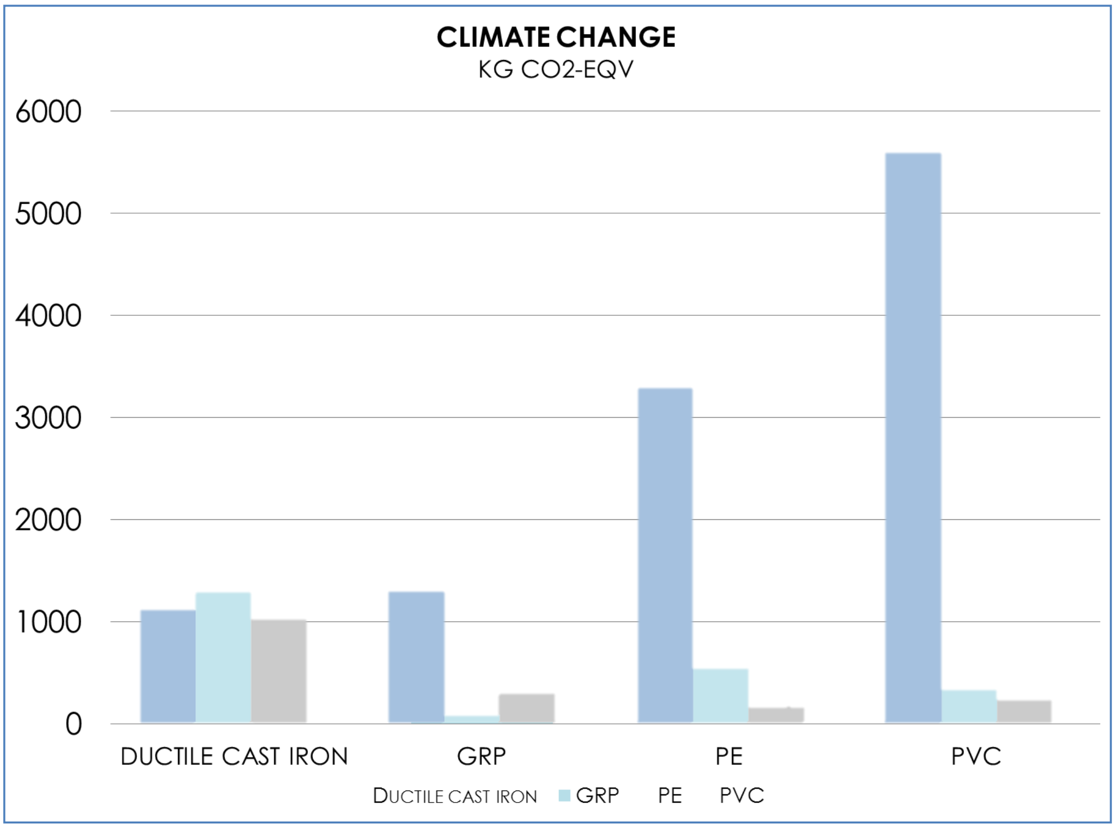


FIGURE 6.5 – IMPACT OF THE PIPE MATERIALS ON THE ENVIRONMENTAL INDICATOR CLIMATE CHANGE

Mineral depletion

Figure 6.6 shows the impact of the pipe materials on the environmental indicator *mineral depletion*. The figure is completely dominated by the contribution from the pipe material ductile cast iron. It is primarily the *raw materials* life cycle phase that contributes, although the contributions from the energy and transportation phases are larger than for the other pipe materials. GRP accounts for the next largest contribution from raw materials and transportation, and the next largest contribution overall, although the energy phase has a negligible contribution. PE performs best with the lowest overall consumption, while PVC has slightly higher values for the raw materials and transportation phase. Note that the total mineral depletion associated with ductile cast iron pipe is over 10 times greater than that for GRP, PE and PVC combined.

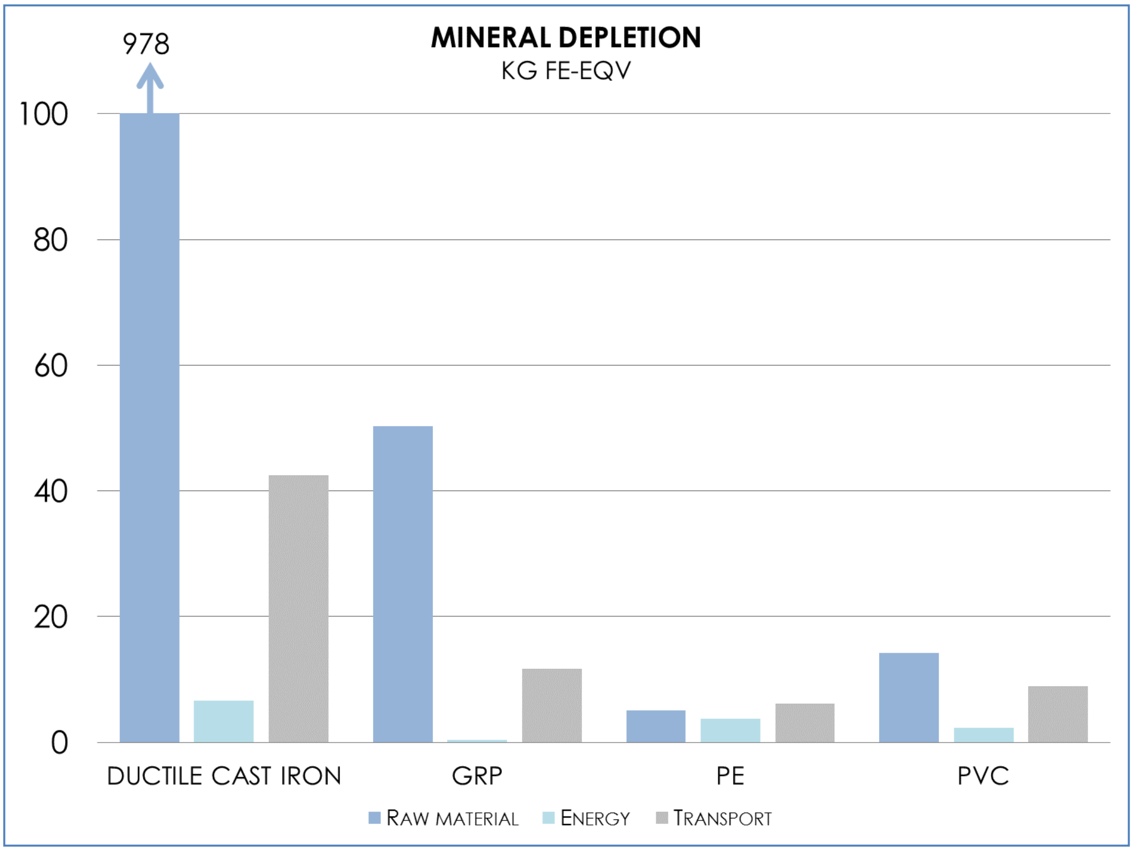


FIGURE 6.6 – IMPACT OF THE PIPE MATERIALS ON THE ENVIRONMENTAL INDICATOR MINERAL DEPLETION
NOTE THAT THE CONTRIBUTION FROM RAW MATERIALS FOR DUCTILE CAST IRON IS GREATER THAN THAT SHOWN IN THE RESPECTIVE COLUMN

Fossil fuel consumption

Figure 6.7 shows the impact of the pipe materials on *fossil fuel consumption*. For this environmental indicator, the figure shows that it is the raw materials associated with the plastic-based pipe materials that contribute the largest percentage. PE pipe accounts for the largest impact from raw materials, and also overall for all life cycle phases. The contribution of PVC is less, although the impacts are still significantly greater than those from ductile cast iron and GRP. Ductile cast iron is the raw material with the smallest impact from the raw materials life cycle phase, while GRP contributes the smallest impact in total. Overall, the contributions from GRP and ductile cast iron for this environmental indicator are less than the contribution from PE alone.

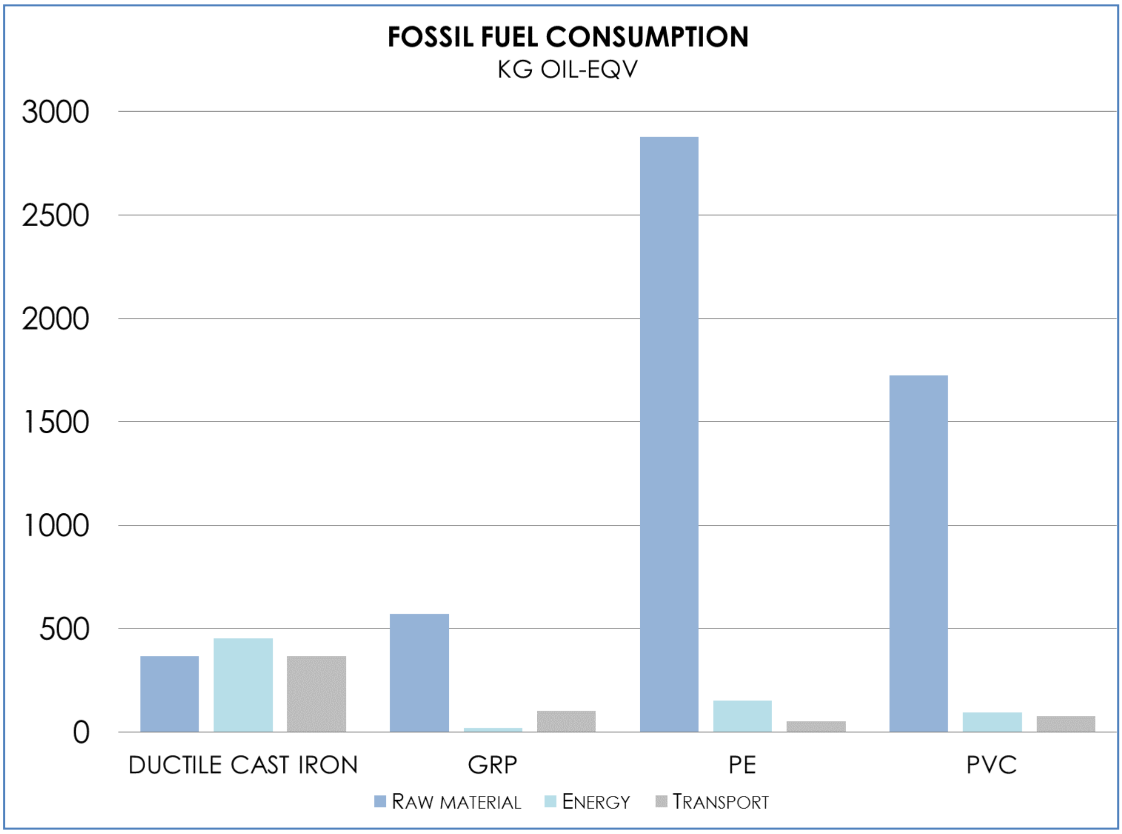


FIGURE 6.7 – IMPACT OF THE PIPE MATERIALS ON FOSSIL FUEL CONSUMPTION

RECIPE ENDPOINT

Human health

Figure 6.8 shows how the various pipe materials affect the impact category *human health*. Both the internal distribution and the overall impact are similar to the results for climate change, as graphically presented in Figure 6.5. PVC stands out with a large contribution from the raw materials life cycle phase, which is more than twice the corresponding contribution from PE. The impact percentage from the energy phase of the pipes is greatest for ductile cast iron and least for GRP. Ductile cast iron has the next largest total contribution, although PE is little better. GRP is the material that comes out best.

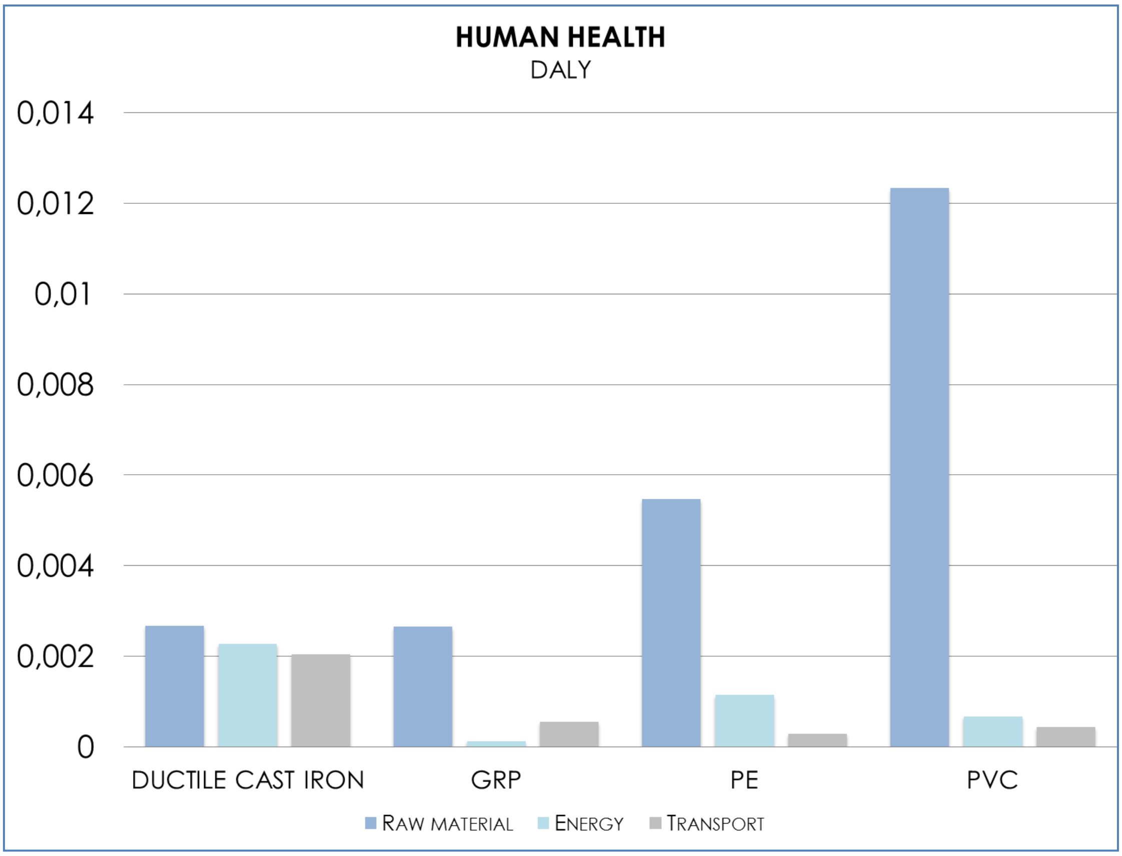


FIGURE 6.8 – IMPACT OF THE PIPE MATERIALS ON THE IMPACT CATEGORY HUMAN HEALTH

Ecosystems

The results for the impact category *ecosystems* are presented in Figure 6.9. The distribution from the preceding impact category is repeated fairly consistently. The values for PVC are lower in this case in relative terms, but still significantly higher than for the other materials. The contribution from PE is the next largest, primarily as a result of the raw materials life cycle phase. The contribution from ductile cast iron is marginally less, with the bulk of the impact stemming from the energy and raw materials phase, and slightly less from the transportation phase. GRP performs best with by far the lowest total contribution, the majority of which originates from the raw materials life cycle phase and only a negligible contribution from the energy phase.

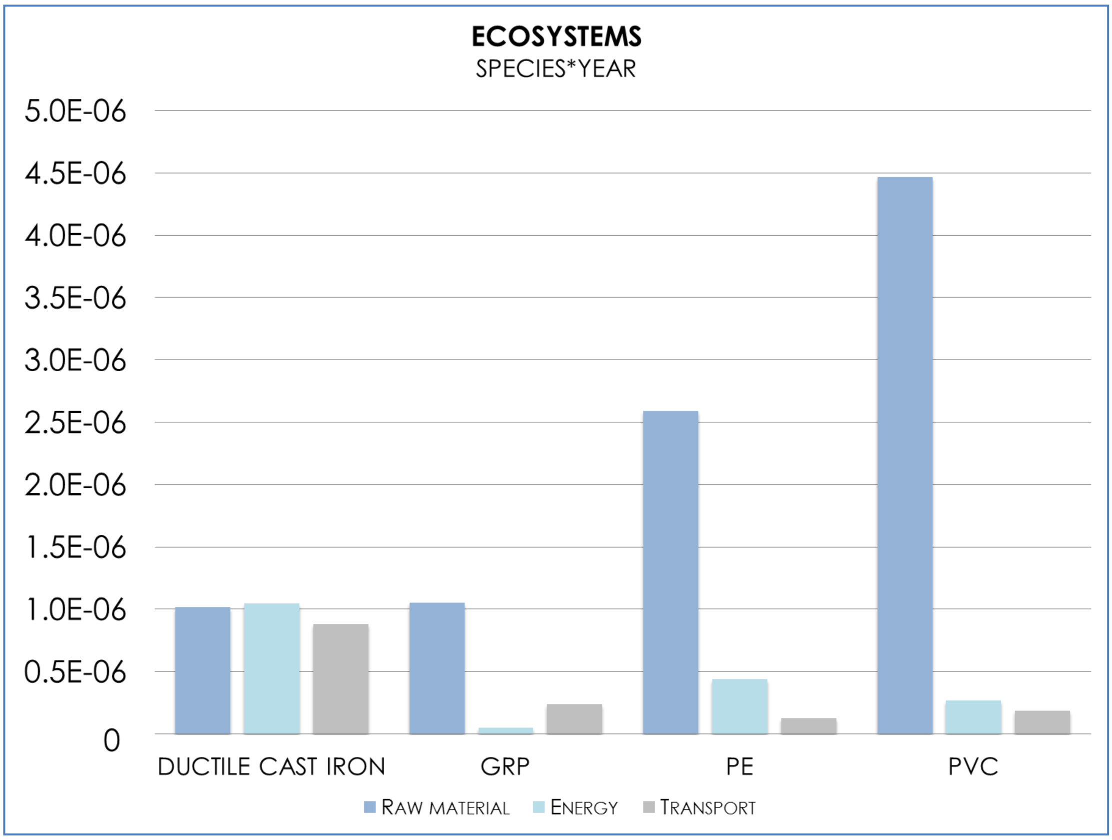


FIGURE 6.9 – IMPACT OF THE PIPE MATERIALS ON THE ECOSYSTEMS IMPACT CATEGORY

Resource depletion

Figure 6.10 presents the results from ReCiPe's endpoint category *resource depletion*. The figure indicates that it is the raw material life cycle phase of plastic pipes that dominates this impact category. Unlike the other two impact categories, the greatest contributions in this case come from PE pipe, while PVC represents a significantly smaller percentage with the next largest contribution. The total impact from each of the pipe materials differs, and the GRP pipe represents the smallest percentage. The largest contribution, from the pipe material PE, is a resource depletion corresponding to USD 49,000, while the contribution from PVC is USD 30,500. The impacts from ductile cast iron are considerably less than those from PVC, but still almost twice those from GRP.

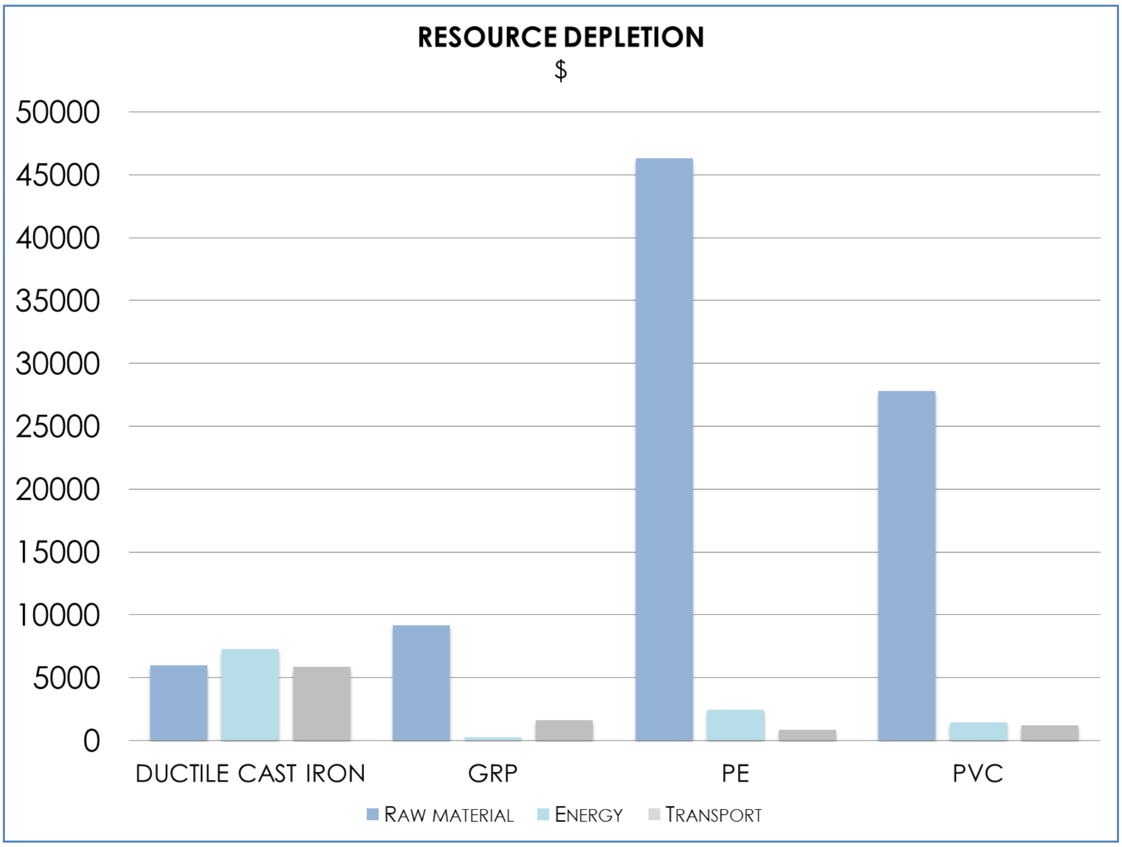
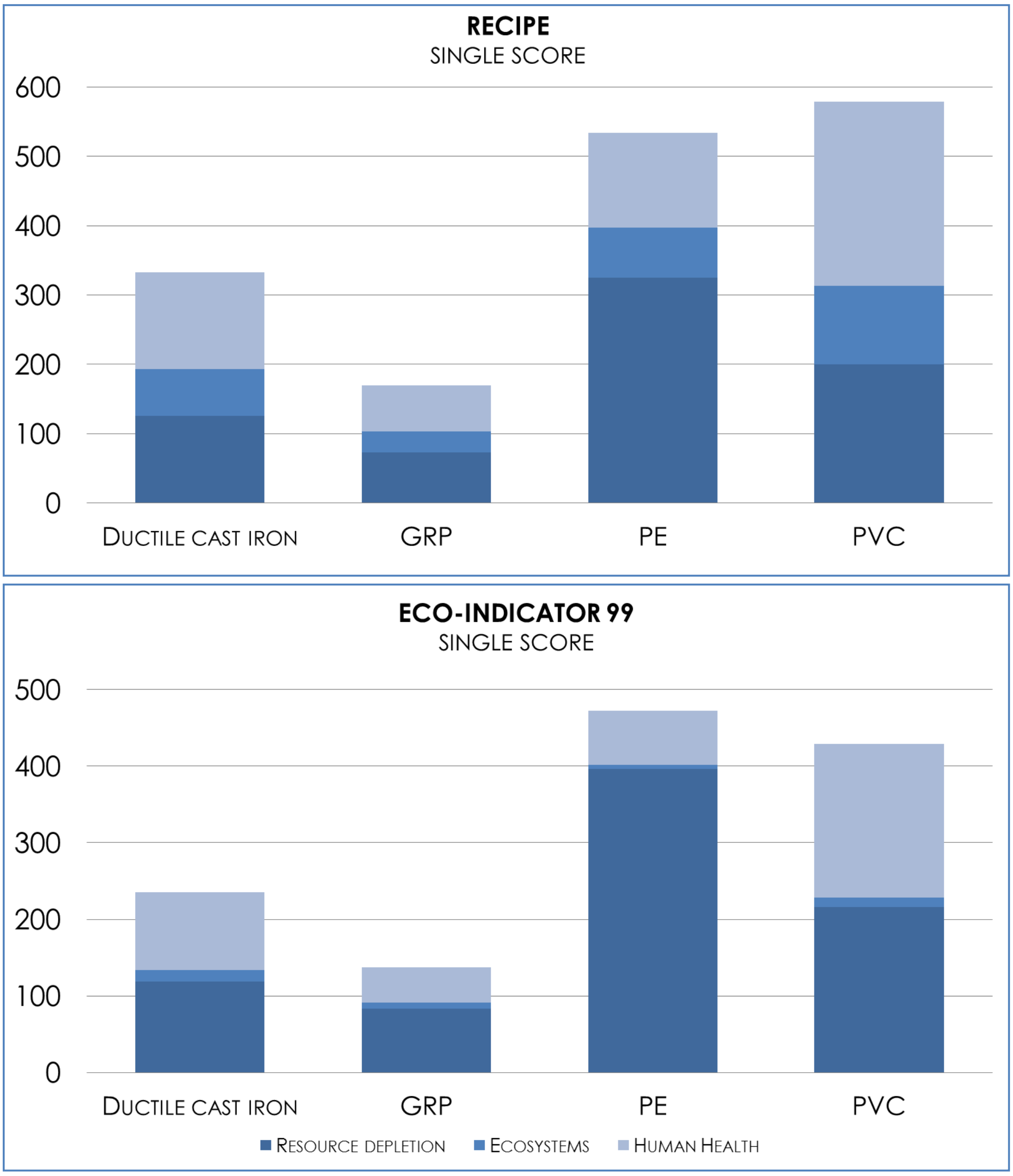


FIGURE 6.10 – IMPACT OF THE PIPE MATERIALS ON THE IMPACT CATEGORY OF RESOURCE CONSUMPTION

SINGLE SCORE

Figures 6.11 and 6.12 show the single score values for each of the pipe materials, broken down according to the three impact categories of human health, ecosystems and resource depletion. The figures show that the total for each of the pipe materials is distributed fairly equally. The contribution from resource depletion is largest in both cases. The contribution from the ecosystems impact category is smallest, but is greater in ReCiPe than in Eco-Indicator in relative terms. The biggest difference between the results is that PVC performs worst with the highest total in ReCiPe, whereas PE has the highest total in Eco-Indicator. GRP has the lowest single score value in both cases.



FIGURES 6.11 AND 6.12 – SINGLE SCORE VALUES FOR THE PIPE MATERIALS IN RECIPE AND ECO-INDICATOR 99

6.3 SENSITIVITY ANALYSES

Due to uncertainty in the data set and poor correspondence between information from different suppliers, it was decided to consider the importance of changes in input values for individual elements in the analyses. In this regard, the results will primarily be presented for the environmental indicator climate change, as this is a politically accepted and frequently used parameter that is often referred to in connection with sustainability (FN 2012a; Utenriksdepartementet 2011).

DISTRIBUTION BETWEEN SCRAP IRON AND PIG IRON IN DUCTILE CAST IRON PIPE

As mentioned previously, the ratio between scrap iron and pig iron in ductile cast iron pipe varies somewhat, and the percentage of scrap iron has been stated as ranging between 50% and 90%, depending on the manufacturer and availability on the international scrap iron market. As a result, an analysis was carried out in order to compare the impact from a pipe containing 90% scrap iron (as used in the other analyses) and a pipe containing equal proportions of scrap iron and pig iron. The results are presented for all parameters, i.e. the three environmental indicators in the ReCiPe midpoint analyses and the environmental categories in the endpoint analyses. Table 6.5 shows the impacts from the raw material iron and the total impact for ductile cast iron pipe with scrap iron percentages of 90% and 50%.

TABLE 6.5 – TOTAL IMPACT OF PIG IRON AND SCRAP IRON FOR TWO DIFFERENT DISTRIBUTIONS

		90% SCRAP IRON 10% PIG IRON		50% SCRAP IRON 50% PIG IRON		
		FROM IRON	TOTAL CONTRIBUTION	FROM IRON	TOTAL CONTRIBUTION	INCREASE
CLIMATE CHANGE	[KG CO_2 EQ.]	733	3,370	2,663	5,300	1.57
MINERAL DEPLETION	[KG FE EQ.]	549	1,030	2,228	2,710	2.63
FOSSIL FUEL CONSUMPTION	[KG OIL EQ.]	251	1,190	920	1,860	1.56
HUMAN HEALTH	[DALY]	2.0E-03	7.0E-03	7.2E-03	1.2E-02	1.75
ECOSYSTEMS	[SPECIES*YEARS]	6.7E-06	2.9E-05	2.3E-05	4.6E-05	1.59
RESOURCE DEPLETION	[USD]	4,075	19,200	14,984	30,100	1.57

The results indicate that increasing the percentage of pig iron from 10% to 50% increases the impacts for all parameters by a factor of between three and four, although this increase only applies to the contribution from iron. As indicated by the individual results, the *raw materials* life cycle phase is not the dominant phase with regard to the impact from ductile cast iron, and the table above indicates that the total contribution increases by a factor of around 1.6. The exception is the environmental indicator *mineral depletion*, where the contribution from the raw materials life cycle phase basically accounts for over 90% of the total. In this case, the total contribution increases by a factor of 2.6.

ENERGY LIFE CYCLE PHASE

The type of energy used for the production of pipes may be decisive for the analysis results, and as a result it was decided to use a common European electricity mix for all pipe materials as described in the method section.

Two separate analyses were performed for all pipe materials using energy mixes from Sweden and Poland in order to consider the difference that the origin of the electricity can make. Sweden primarily generates hydro and nuclear power, while the main energy source for electricity generation in Poland is coal. This results in two very different impact pictures.

Table 6.6 shows the distribution of various energy sources used for electricity generation in Sweden and Poland, in addition to ENTSO-E (the European network of transmission system operators for electricity), which is used as an energy mix for the other analyses. The statistics for ENTSO-E date from 2009, while the statistics for Poland and Sweden date from 2008 (Itten et al. 2012).

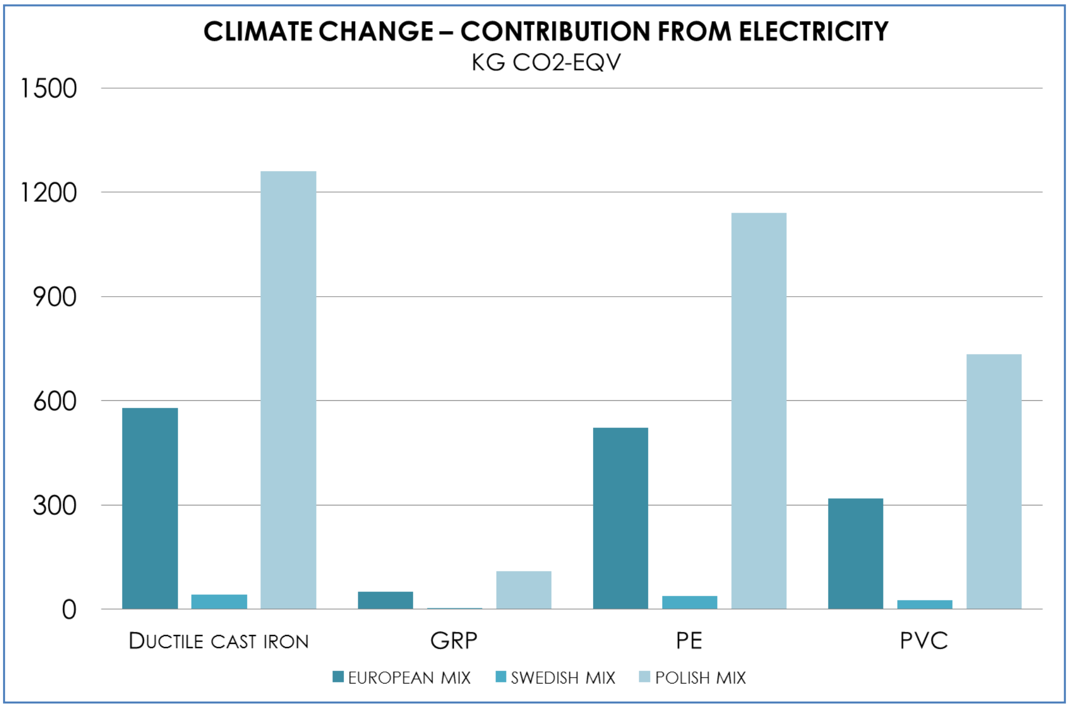
TABLE 6.6 – OVERVIEW OF THE DISTRIBUTION OF ENERGY SOURCES FOR THE ELECTRICITY GENERATION OF VARIOUS REGIONS (AFTER ITTEN ET AL. 2012)

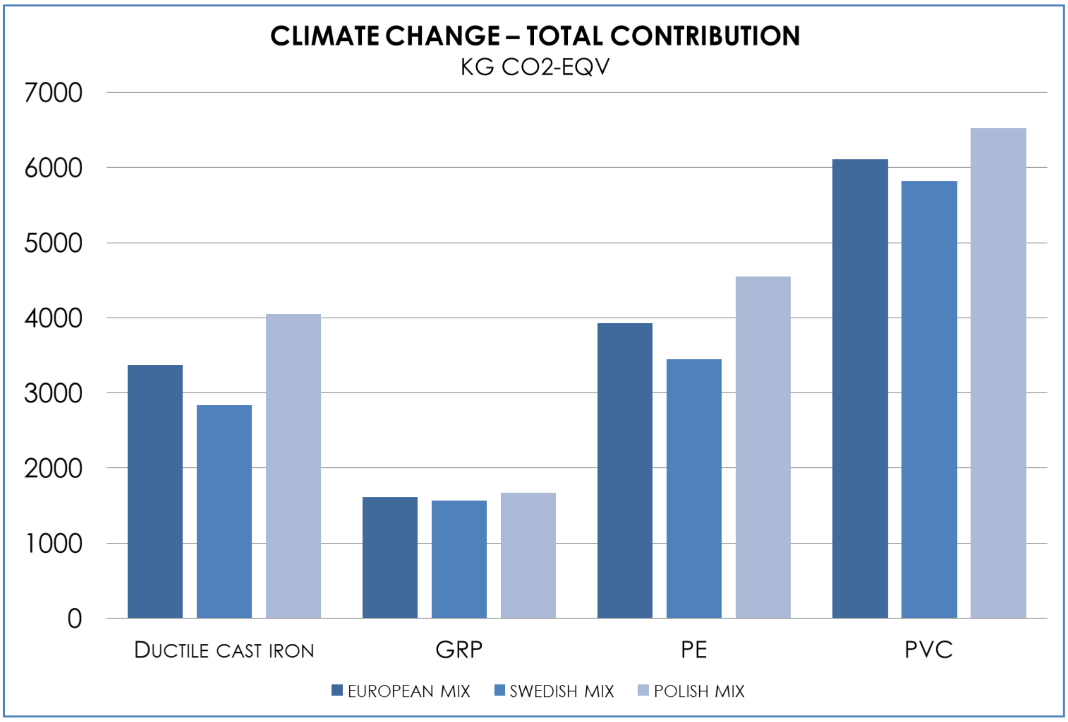
ENERGY SOURCE	ENTSO-E	SWEDEN	POLAND
Fossil fuel	49.5%	2.5%	94.5%
Hydroelectric power	16.5%	47.5%	2%
Nuclear power	26.5%	41.5%	0%
Renewable sources	6%	7.5%	2.5%
Waste	1%	1%	0.5%
Other	0.5%	0%	0.5%

As the table shows, Sweden and Poland are opposites with regard to energy sources for electricity generation, while the European mix generally falls somewhere between the two.

The results are presented in Figure 6.13, which shows the contribution that the various pipe materials make to climate change *from the energy life cycle phase* for the two national energy mixes and the European mix, which was used in the other analyses.

Note that gas has been excluded from the energy phase for ductile cast iron and GRP, even though it is included in the energy consumption for the production of these pipes. Thus, the contribution from gas has been omitted, but will be constant in all three cases. Figure 6.14 shows the *total impacts* that each of the pipe materials have for climate change with the three different energy mixes.





FIGURES 6.13 AND 6.14 – IMPORTANCE OF VARIOUS ENERGY MIXES
ON THE ENVIRONMENTAL INDICATOR CLIMATE CHANGE

The figures show the contribution to the environmental indicator climate change for the four pipe materials with three different electricity mixes. Figure 6.13 provides a good illustration of how great the differences can be between the electricity mix of different regions in terms of emissions of CO_2 equivalents. Furthermore, Figure 6.14 shows that the choice of electricity mix can be decisive for the outcome of the total impacts in this study if different electricity mixes are used for the various pipes.

TRANSPORTATION LIFE CYCLE PHASE

As described in section 4.2, product-specific transportation information has been used in the analyses in order to obtain genuine input data. The problem then is that the transportation life cycle phase for each of the pipe materials is directly associated with a specific manufacturer and factory, and cannot be considered generally. For information purposes, GRP has the longest transportation stages in the analyses, for both raw materials and finished pipes. The PE pipes have the shortest transportation distance overall. Figure 6.15 shows the impact of each of the pipe materials on the environmental indicator climate change, both with and without contributions from the transportation life cycle phase.

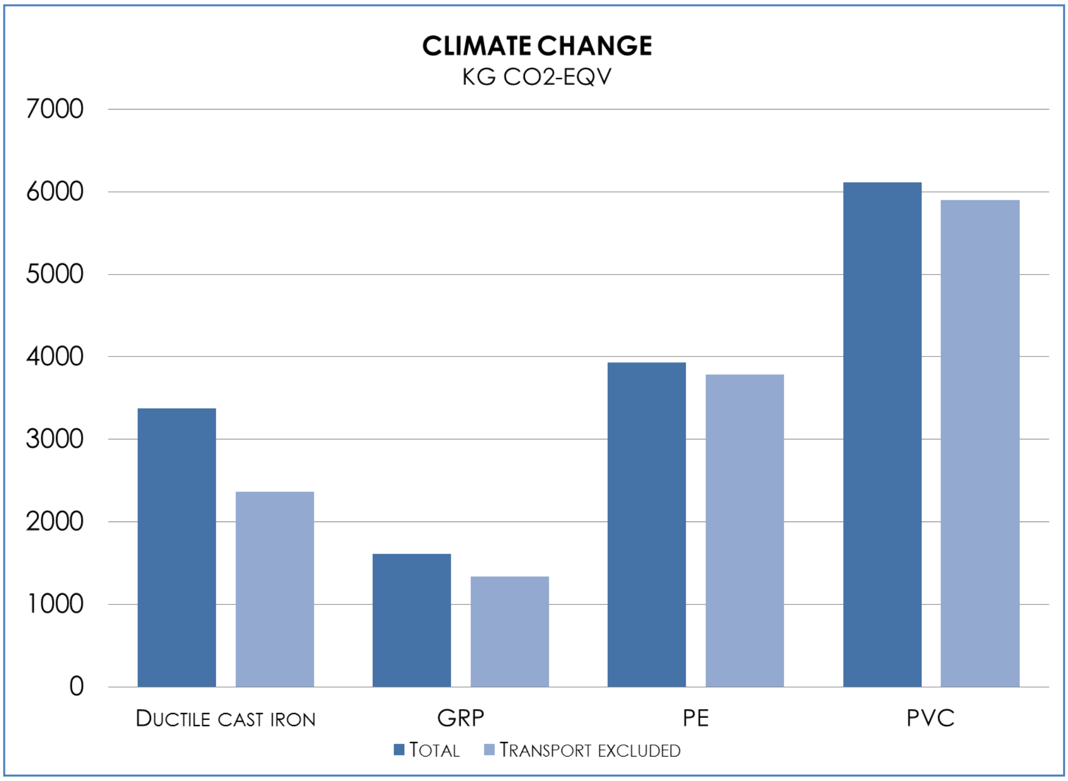


FIGURE 6.15 – IMPACT OF THE PIPE MATERIALS ON CLIMATE CHANGE WITH AND WITHOUT THE TRANSPORTATION PHASE

The results show that excluding the transportation life cycle phase makes the biggest difference for ductile cast iron, and the smallest for PE, which has the shortest transportation distance in the study. The total distribution between the pipe materials is unchanged.

It is usual in life cycle analyses to calculate transportation as the product of distance and the weight of what is being transported (tonnes*km). Thus, the weight of the pipe materials will make a difference if all of the pipes are transported a specific distance using the same means of transportation. In order to obtain an indication of how pipe transportation varies for the various pipe materials, an example is used here to show the relationship between these. If pipes corresponding to a functional unit (100 metres) are to be transported 100km, the number of tonnes*km will be as follows:

TABLE 6.7 – OVERVIEW OF HOW THE WEIGHT OF THE PIPE MATERIALS AFFECTS THE TRANSPORTATION PHASE

PIPE MATERIAL	WEIGHT [KG/100 METRES]	TONNES*KM
Ductile cast iron	3700	370
GRP	650	65
PE	1690	169
PVC	1160	116

For a specific distance using a specific means of transportation, the contribution from the transportation life cycle phase will be greatest for cast iron and least for GRP. For PE and PVC, the impacts will be of the order of just over half and a third respectively of the contribution for ductile cast iron.

INCREASED PIPE DIAMETER

The impact picture may be different when the pipe diameter is changed, and as a result pipes with an internal diameter of 200mm and 600mm were also analysed in this study. Figure 6.16 shows the impacts for the environmental indicator climate change for the pipe materials ductile cast iron, GRP and PE in both dimensions. Figure 6.17 shows how the wall thickness of these pipes change as their diameter increases. PVC pipe has been omitted, as this type of pipe cannot be supplied in dimensions larger than DN 400.

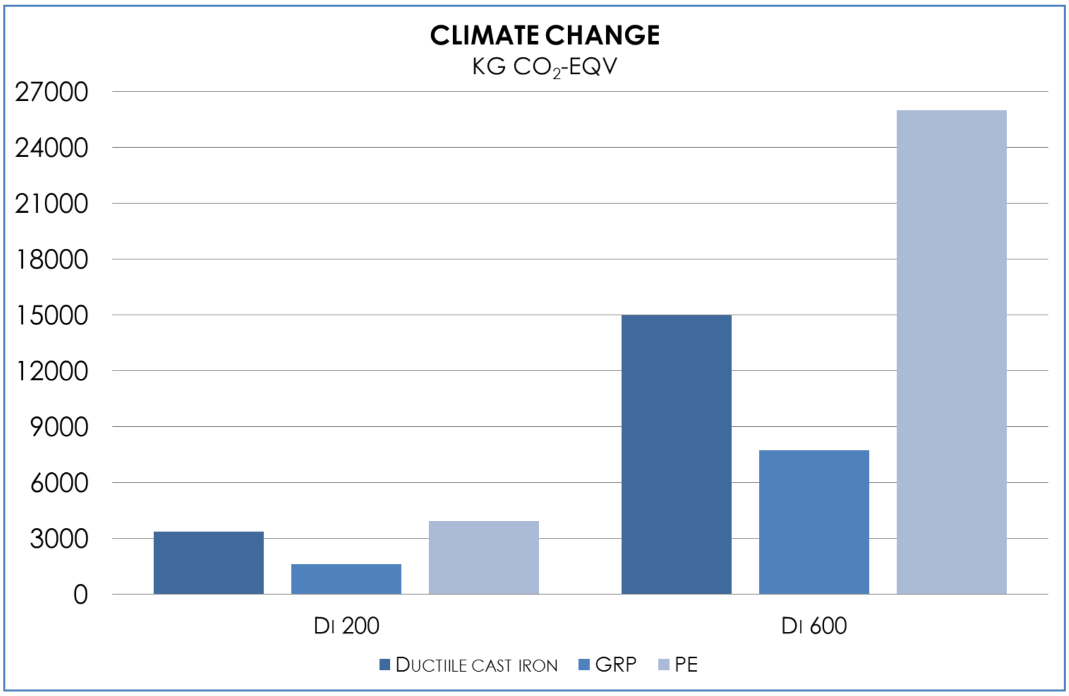


FIGURE 6.16 – IMPACT OF THE PIPES ON CLIMATE CHANGE

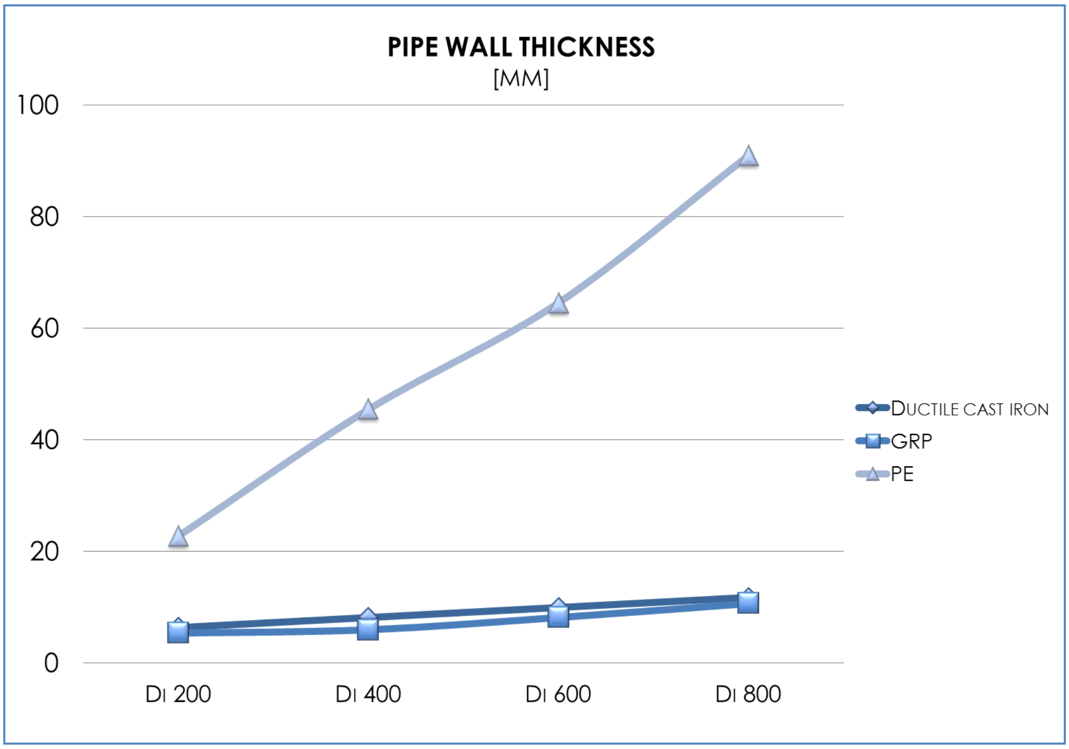


FIGURE 6.17 – PIPE WALL THICKNESS AS A FUNCTION OF INTERNAL DIAMETER

As can be seen in both figures, PE shows the biggest change as pipe diameter increases. The relationship between ductile cast iron and GRP is fairly constant, and the wall thickness is remarkably similar for the pipe dimensions that were studied. However, it would appear that the impact on climate change somewhat increases for GRP compared with ductile cast iron.

7 DISCUSSION

7.1 INDIVIDUAL RESULTS

The individual results are not the main focus of this comparative study. Nevertheless, they provide an overview of the aspects associated with the life cycle of the pipes that contribute to the various environmental indicators, which is worthy of comment.

In broad terms, the individual results show that the raw materials life cycle phase is dominant for the plastic materials PVC and PE, along with GRP, which has a polyester content of 34% by weight. Ductile cast iron, which was the heaviest material in the study, has the largest contribution, from both the energy and transportation phases.

All pipe materials show fairly consistent results as regards the internal distribution between the impact of the life cycle phases. One exception is the environmental indicator *mineral depletion*: In this case, the raw material percentage from ductile cast iron increases considerably, while at the same time, the contribution from raw materials for both PE and PVC is considerably less than in the other results. GRP shows little change for this environmental indicator, because the raw material glass fibres contributes to a larger impact here than in the other results, which makes up for the smaller contribution percentage of the polyester.

A number of previous studies have concluded that the majority of environmental pressures associated with drinking water pipes originate from processes relating to the raw materials used in the pipe materials (Dennison et al. 1999; Friedrich et al. 2007). A Spanish study from 2005 found that the largest share of impacts originates from the phase where the pipes are in use, while the processing of the raw materials accounts for the next largest share (Recio et al. 2005). These results correspond fairly well with the findings of this study. The exception is ductile cast iron, which has a greater contribution percentage from the energy phase in many cases. This may perhaps be explained by the fact that scrap iron is primarily used in the analysis, which consistently results in a lower impact because the raw material processing is carried out at an earlier stage and does not contribute to such a great extent when the iron is subsequently recycled. Another possible explanation is that some of the material processing takes place during the production process itself when it is heated to 1,500°C, which contributes to the considerable impact from energy consumption. The relatively large percentage from the transportation phase must first and foremost be explained through the fact that ductile cast iron is the heaviest material in the study, and thus contributes a larger impact from the transportation of both raw materials and finished pipes than the other pipe materials.

A recent study (Du et al. 2012) considered the life cycle phases of pipe production, transportation, installation and use for various pipe materials. This included both the processing of raw materials and pipe production during the production phase. The study concluded that this is the dominant phase with regard to environmental impacts. The results correspond well with the findings of this study, although a direct comparison may not be drawn, as the life cycle phases of installation and use have been excluded here.

7.2 COLLATED RESULTS

The collated results aim to provide answers to the question posed in this thesis, and an examination of the results from section 6.2 reveals a number of points that are immediately obvious. The pipe material GRP clearly distinguishes itself in a positive direction, and is the material that is uniformly associated with fewest impacts. Furthermore, it is clear that the difference between the impacts from the various pipe materials is significant in many cases.

CLIMATE CHANGE

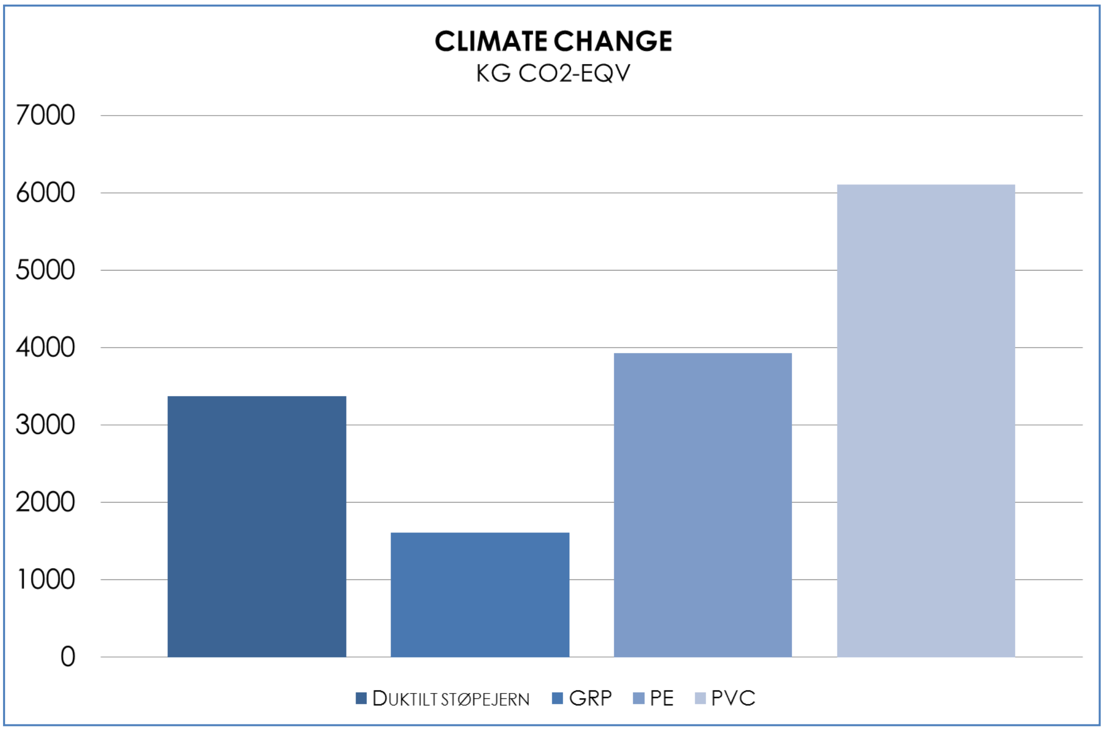


FIGURE 7.1 – IMPACT OF THE PIPE MATERIALS ON THE ENVIRONMENTAL INDICATOR CLIMATE CHANGE

There has been considerable discussion over the importance of CO_2 emissions in connection with the greenhouse effect since the late 1990s. The Kyoto Agreement, which entered into force in 2005, imposes a requirement for the reduction of emissions from industrialised countries, and has helped to put GWP on the environmental policy agenda (Klif 2012). Climate (change) is often cited in the context of sustainability (FN 2012a; Utenriksdepartementet 2011), and in this way is a relevant environmental indicator. This makes it interesting to consider the differences between the four pipe materials with regard to potential climate change. A graphical presentation of the results is shown in Figure 7.1 above.

The results illustrate that PVC, with associated emissions of over 6,000kg CO_2 equivalents, contributes the most to this environmental indicator. This contribution is actually almost four times as great as that from GRP, which with 1,610kg CO_2 equivalents, represents the smallest impact.

The outcome does not coincide with the findings of previous studies as regards the raw materials' emissions of kg CO_2 equivalents, which are illustrated in Table 7.1:

TABLE 7.1 – CONTRIBUTION OF THE PIPE MATERIALS TO CLIMATE CHANGE, FINDINGS FROM VARIOUS STUDIES

STUDY	**YEAR**	**CLIMATE CHANGE**	**CAST IRON**	**PE**	**PVC**	**GRP**
This study	2012	kg CO_2 eq./100m pipe	3,370	3930	6110	1610
Du et al.	2012	tonnes CO_2 eq./km pipe	472	218	318	-
Venkatesh et al.	2009	kg CO_2 eq./kg pipe	3.41	2.33	2.36	-
Recio et al.	2005	kg CO_2 eq./3m pipe	681	454	452	-

Note that the results from Venkatesh et al. (2012) in the table are specified as emissions per kg of pipe, unlike the other studies which use emissions per unit length of pipe. None of the studies considered the pipe material GRP, which has no basis for comparison here. The results otherwise do not correspond with the findings of this study. The other studies cover more life cycle phases and other pipe dimensions than this study, and thus some of the explanation for the differences may lie in the varying scope of the analyses.

In the study by Du et al. (2012), the results for pipes with a diameter of 300mm are presented, along with the life cycle phases of production, transportation and installation. The main difference between the analyses in the study performed by Du et al. and the analyses in this study is that the former used 100% pig iron in the production of ductile cast iron pipe.

Venkatesh et al. (2009) specified the results per kg pipe, and did not specify any pipe diameters as a result. It was stated that ductile cast iron was analysed with a raw material distribution of 61% pig iron and 39% scrap iron.

Recio et al. (2005) considered pipes with an internal diameter of around 100mm, but the ductile cast iron pipe has an internal diameter of 125.6mm, which is around 25% larger than PVC and PE at 99.4 and 102.2mm respectively. This must be considered as being a significant difference, as a 25% larger diameter corresponds to a cross-sectional area that is 50% larger, and a pipe with a significantly higher transportation capacity. Furthermore, it is noted that the wall thickness and weight of plastic pipes increase more as the diameter of the pipe increases than is the case for ductile cast iron pipe. It is stated in the study that 100% pig iron was used in the cast iron pipe. These circumstances are all to the disadvantage of ductile cast iron.

Ductile cast iron gives the largest emissions results in the three independent studies, and some of the explanation for this must certainly lie in the high percentage of pig iron used in all three cases. Experience gained through sensitivity analyses in this study suggest that the ratio between pig iron and scrap iron may be decisive for the outcome, and is a possible explanation as to why ductile cast iron has the largest emissions in the three studies. The result from the sensitivity analysis of ductile cast iron with 50% pig iron in this study is emissions of 5,300kg CO_2 equivalents. This is much closer to the emissions percentage from PVC of 6,110kg CO_2 equivalents, although it is still less.

Furthermore, the gap between the magnitude of the emissions from PVC and PE varies between the various studies. Both this study and Du et al. (2012) found that the contribution from PVC is around 1.5 times greater than that from PE, while Recio et al. (2005) arrived at almost identical emission figures for both materials.

It can be seen from the results of this study that the majority of the impact on climate change is due to the life cycle phase *raw materials* for both PE and PVC. Further study of the analysis results indicates that the emissions associated with PVC granules are almost twice those from PE granules, even though the percentage of PVC granulate is less than that of PE granules for the pipes analysed (around 10.5kg and 16.6kg of granulate respectively per metre of pipe).

MINERAL DEPLETION

European industry uses over 20% of global metal production and only produces three percent, a situation which poses a significant financial risk according to the EU (Smelror 2011). The consumption of minerals and metals is therefore a relevant parameter for the assessment of sustainability.

As has been shown by the results of this study, the pipe material ductile cast iron entails by far the largest mineral depletion, which is primarily associated with the raw materials life cycle phase. This result is not particularly surprising given that cast iron is the only metal-based material in the study. Findings from the sensitivity analyses indicate that ductile cast iron with a pig iron percentage of 50% increases mineral depletion by a factor of 2.6 from 1,030 to 2,710 Fe equivalents, compared with a pig iron percentage of 10%. The contribution from iron alone increases by a factor of four. In other words, whether newly processed or recycled raw materials are used may be of great importance for the analysis results generally and mineral depletion in particular.

FOSSIL FUEL CONSUMPTION

Fossil fuels are recognised as a non-renewable resource, and as a consequence of this, efficient energy use and the potential to use renewable energy sources can be a competitive advantage (Norges forskningsråd 2005).

Both PE and PVC are manufactured from petroleum or natural gas, two materials that are defined as fossil fuels. This results in an expectation that these pipe materials will dominate the impacts of fossil fuel consumption. The investigations in this study confirm this expectation, as the results show that the plastic-based pipe materials contribute most to this environmental indicator. The raw materials constitute a significant percentage, and PE has the largest contribution in this regard. The contribution from PVC, which is formed from both ethylene and chlorine gas, is considerably less than that of PE, which is exclusively produced from ethylene gas. The contribution from ductile cast iron primarily stems from the energy life cycle phase, as a result of gas consumption during pipe manufacture.

RECIPE ENDPOINT

The environmental indicators are divided into the three impact categories in ReCiPe of human health, ecosystems and resource depletion. The impacts from all the parameters assessed (see Figure 4.2 for a complete overview) in these three categories are therefore collated here. This must be seen as providing results of some weight, even though no results have been found from other studies with a direct basis for comparison. The pipe material GRP performs best in all three impact categories with by far the lowest impacts. For human health and ecosystems, the impacts are of the order of a quarter of the contribution from PVC, and less than half of the impacts from ductile cast iron and PE. In the case of resource depletion, where PE has the largest contribution, GRP accounts for around a fifth of this.

SINGLE SCORE

The use of single score is of greatest relevance for comparative studies where the aim is to consider the values relative to each other in the systems that are being assessed. It should be noted that the Eco-Indicator 99 method must be used with caution, as it is not sufficiently transparent in accordance with ISO 14044 (Goedkoop & Spriensa 2000). It is nevertheless interesting to compare the single score values from Eco-Indicator and ReCiPe. It is apparent that the results are fairly consistent despite the fact that two different presentation methods have been used: PVC and PE account for the largest total impacts, while GRP performs best. In all cases, the resource depletion impact category contributes most to the total score and the ecosystems impact category contributes least.

SUMMARY

All the environmental parameters assessed, along with the single score values, are presented in Table 7.2. The pipe materials were given a score from 0–3, where 0 is the lowest impact and 3 is the highest.

TABLE 7.2 – SUMMARY OF THE PIPE MATERIALS' DISTRIBUTION IN ALL ASSESSED PARAMETERS

Environmental parameter	DUCTILE CAST IRON	GRP	PE	PVC
Climate change	1	0	2	3
Mineral depletion	3	2	0	1
Fossil fuel consumption	1	0	3	2
Human health	2	0	1	3
Ecosystems	1	0	2	3
Resource consumption	1	0	3	2
ReCiPe single score	1	0	2	3
Eco-Indicator single score	1	0	3	2
TOTAL	11	2	16	19

The table is intended only as a simple way of presenting the overall results, rather than as a definitive answer. The total for each of the pipe materials gives an indication of how the materials are placed relative to each other, but may only be considered as an overview of all the results. Nevertheless, it may be claimed that the table confirms the impression given in the results, namely that the pipe material GRP performs the best, while PVC and PE account for the most significant impacts in most cases.

7. 3 SENSITIVITY ANALYSES

DISTRIBUTION BETWEEN SCRAP IRON AND PIG IRON IN DUCTILE CAST IRON PIPE

It has already been noted in the discussion that the percentage of pig iron used in ductile cast iron is decisive for the environmental loads associated with this pipe material. If the percentage of pig iron in ductile cast iron pipes is increased, all the impacts analysed for will increase considerably. The explanation for this is fairly obvious, as the extraction of pig iron requires more energy and resources than the processes associated with the handling of scrap iron. Thus, it is worth noting that even with the increase in the impacts associated with a pig iron percentage of 50%, PVC will perform worse for the environmental indicators climate change and fossil fuel consumption. Regardless of these results, the aim of utilising the highest possible scrap iron percentage in pipe production is limited only by the amount that is available on the market.

ENERGY LIFE CYCLE PHASE

The importance of energy use is obvious if the steadily rising energy consumption of industrialised society is considered. Given the scarcity of resources, it is advantageous to use both resources and energy sources in the best possible way, from both a socio-economic and an environmental perspective. Energy-efficiency in industry is a reasonably effective measure with limited political controversy in order to bring about sustainable energy use (SINTEF 2011).

Different energy sources contribute to different impacts, and whether national (country of production) or regional (European) electricity mixes are used can have consequences for the outcome of an LCA (Stokes & Horvath 2005).

The investigations in this study show that the type of electricity mix that is used can be decisive for the outcome, and the choice of country of production with its associated energy mix can therefore be a competitive advantage.

Findings from previous studies (presented in the literature study) indicate that ductile cast iron has the highest energy consumption per metre of pipe. This coincides with the input data relating to electricity and gas consumption used in this study. However, these results can be difficult to compare directly, as the analyses vary considerably in scope.

In general, it can be said that the raw material iron, in the form of either pig iron or scrap iron, is less processed than the plastic materials used in other forms of pipe production. This means that more energy is consumed during the underlying processes for plastic raw materials, whereas considerably more energy is consumed during the actual production process for cast iron pipes than for the other pipe materials. Furthermore, the production temperature is highest for ductile cast iron. The production process for GRP, which has the lowest contribution from energy consumption, uses the lowest temperature of the pipe materials which were analysed, and GRP is also the lightest material in the study. GRP is the only composite material covered in the study. It is manufactured using a winding process around a core, unlike the other production processes where the pipes are cast or extruded. These factors are likely to be a factor in the differences in energy consumption.

TRANSPORTATION LIFE CYCLE PHASE

Previous studies have concluded that the transportation phase is of little importance as regards the total environmental impacts associated with water and sewerage pipes (Du et al. 2012; Recio et al. 2005). This corresponds well with the results presented in the previous section, but the results also show that ductile cast iron has a considerably larger contribution from this life cycle phase than in the case of the other three pipe materials. PE has the smallest contribution from the transportation phase.

The transportation stages have been specifically calculated for the producer/supplier used as a source for each of the raw materials. Estimating the mean transportation distance for raw materials is difficult, as the distance involved often varies with availability in the market. Specific data have therefore been used. This means that the analysis results cannot be considered as being entirely general. Nevertheless, it would be incorrect to exclude the transportation phase completely, as material weight is a decisive factor in connection with the calculation of the contribution from this phase. Examination of how the weight of the pipe materials affects the transportation phase for a particular distance shows that the impact of ductile cast iron is around twice that of PE, three times that of PVC, and more than five times that of GRP, the lightest material in the study.

The collated results in this study show that the transportation phase for ductile cast iron in all cases accounts for more than four times as much as the transportation phase for PE and PVC. In other words, it is unlikely that the impacts from transportation in connection with the use of other input data will alter the distribution between the total impact of the pipe materials.

LARGER PIPE DIMENSIONS

This study essentially aims to cover pipes with an internal diameter of 600mm in addition to 200mm in order to assess how the impacts are distributed for larger pipe diameters. As stated in the life cycle descriptions in Chapter 5, an exact specification of the raw material composition has only been given for GRP pipe, as this distribution changes with larger pipe dimensions. Only a percentage distribution by weight has been specified for the other pipe materials. In cases where the material composition is the same for small and large diameters, the increase in impact can be calculated simply on the basis of the pipe's increase in weight from one dimension to another. Table 7.3 shows how the weight of the pipe materials increases from D_i 200 to D_i 600.

TABLE 7.3 – INCREASE IN PIPE MATERIAL WEIGHT WITH INCREASING DIMENSIONS

PIPE MATERIAL	D_i 200 [KG/METRE PIPE]	D_i 600 [KG/METRE PIPE]	INCREASE [D_i 600/D_i 200]
Ductile cast iron	37	168	4.5
GRP	6.5	30.6	4.5
PE	16.9	112	6.6

As is apparent from the table, ductile cast iron pipes and GRP pipes increase the weight by a factor 4.5, whereas PE pipes increase the weight by a factor of 6.6. This means that the relationship between the impacts from ductile cast iron and GRP will remain approximately the same, while the impact of the PE pipe relative to the other two materials will become considerably larger as the pipe diameter increases.

Du et al. (2012) considered the environmental indicator climate change and the importance of different materials and larger pipe dimensions. The study concluded that ductile cast iron is the pipe material which causes the greatest environmental load up to a diameter of 610mm, and that for diameters larger than this, PVC accounts for the largest emissions of CO_2 equivalents. This finding can be explained by the fact that the wall thickness of plastic pipes increases dramatically for larger dimensions, in contrast to ductile cast iron, which has a more moderate increase in wall thickness. This supports the argument that plastic pipe (PE pipe in this case) will have a larger environmental impact relative to ductile cast iron and GRP at DN 600 than at DN 200. This is also confirmed by the findings from the sensitivity analysis conducted as part of this study.

It is apparent from the relationship between the weight percentages of the raw materials for GRP pipe at DN 200 and DN 600 that the larger pipe diameter consists of a higher percentage of glass fibre and a smaller percentage of polyester and sand. A rough estimate would suggest that the total impact from GRP relative to ductile cast iron will be somewhat smaller for the environmental impacts, which is dominated by the plastic raw material polyester, and increases as regards mineral depletion, among other things, due to the higher percentage of glass fibres at DN 600 relative to DN 200.

7.4 UNCERTAINTY

INPUT DATA

The element of uncertainty in this study is linked to the quality of the input data used in the analyses. A comparative study is dependent on reasonably comparable underlying data for each of the units analysed. This cannot be taken for granted in cases where the sources used represent different companies with their respective data sets and availability. For example, the information concerning raw materials is presented either as concentrations of various elements expressed as a percentage, or as an estimated distribution by weight between the various materials manufactured. This results in two very different approaches to the construction of the analysis, where the former is more accurate with regard to the pipe's *specific composition*, while the latter is more precise with regard to the *raw materials* that must be placed under the raw materials life cycle phase in the analysis. Energy consumption is specified as either the number of kWh consumed per kg of pipe, or the factory's total annual consumption. Thus, the approach to the figures adopted for each functional unit differs for each of the pipe materials. As stated in the life cycle descriptions, certain assumptions have also been made as regards the input data for the analyses.

The validity of the results must be assessed on the basis of the fact that the input data for the various analyses varies in origin and exists in different forms before being adapted for use in SimaPro. This complicates the basis for comparison and contributes to the greatest element of uncertainty in the underlying data. Nevertheless, most of the results are sufficiently clear that any errors in the data set must be significant as regards the level of impact if they are to alter the outcome as regards which pipe materials perform the best and worst.

SOURCES

Access to valid and sufficiently detailed numerical data for the analyses' input data was by far the biggest challenge in the work on this Master's thesis. There are confidential aspects to the manufacture of certain pipe types, which had to be addressed by using approximations in the analyses. In some cases, the author was also unable to obtain responses to key questions, even though a number of independent producers and suppliers were contacted.

A study such as this is dependent on manufacturers and suppliers providing information regarding the raw materials and processes involved in pipe manufacture. Aspects that are considered to be commercial secrets or competitive advantages may be completely unavailable, depending on who is requesting the information.

7.5 PROPOSALS FOR FURTHER WORK

The availability of more time would enable more consistent input data to be obtained for the analyses, for each specific pipe material and pipe diameter insofar as such information is available to 'third parties' wishing to consider the issue. As mentioned previously, access to input data may be limited due to the reluctance of manufacturers to provide details concerning matters they perceive to be commercial secrets. Based on the experiences of obtaining information gained in this study, it is nevertheless believed that sufficient time and communication with people with first-hand information could prove to be crucial in gaining access to relevant input data. Analysing more pipe dimensions may also be of greater relevance in cases where such information exists.

Furthermore, it may be interesting (not to mention relevant) to provide supplementary analyses for sewerage pipes.

There are also a number of other aspects which could be studied in more detail on the basis of the findings from this thesis. For example, it would be possible to include joint and sleeve arrangements for longer pipe stretches based on the chosen functional unit. It may also be appropriate to conduct life cycle analyses which include internal and external pipe coatings. A British study from 1999 found that zinc layers on ductile cast iron pipes is a significant contributor to energy consumption due to the manufacturing process that is used (Dennison et al. 1999). Except in the abovementioned study, it has not been common practice to include pipe coatings in life cycle analyses for pipe materials.

It would also be possible to extend the life cycles to include the pipes' use phase in order to consider whether there is a significant difference between the pipe materials in terms of energy and resource use linked to the daily operation of the pipe network.

8 CONCLUSION

The life cycle assessments of pipe materials for the distribution of drinking water, including ductile cast iron, glass fibre reinforced polyester, polyethylene and polyvinyl chloride indicate that there are significant differences between the materials with regard to the environmental impacts that were studied.

The results show that GRP indisputably results in least environmental load with regard to the indicators investigated. The results are not as consistent with regard to the materials that perform least well, but it is primarily PE and PVC that account for the most significant impacts, which are of the order of 2–4 times greater than those caused by GRP.

The raw materials life cycle phase dominates the impact picture for all plastic-based pipe materials, while the distribution is more even between the contributions for the raw materials, energy and transportation phases for ductile cast iron.

The analyses were performed for pipes with an internal diameter of 200mm. Increasing the pipe dimension alters the impact picture because the wall thickness and weight of PE (and PVC) pipes increase to a greater extent than in the case of the other two materials as pipe diameter increases. The outcome changes to the disadvantage of the plastic materials. A comparison of the percentage increase by weight from one dimension to another for each of the pipe materials provides a good indication of how the impact picture changes.

The results are sensitive to the energy mix that is used in the analyses, and less sensitive to changes in the transportation life cycle phase.

On the basis of these findings, it would seem appropriate to take into account sustainability considerations when choosing pipe materials. The results primarily indicate that there are significant differences between the pipe materials that were analysed. Furthermore, most of the impacts are associated with the life cycle phases raw materials and energy consumption, irrespective of the pipe material. This means that materials can be chosen based on environmental factors associated with the raw materials used in the pipe material and manufacturing processes, irrespective of how far the pipes may have to be transported. The sensitivity analyses show that the impact relationship between the pipe materials changes as the pipe dimensions increase. This implies that the differences between the various pipe materials with regard to a number of the environmental indicators are even more significant in the case of larger pipe diameters.

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INPUT DATA: TRANSPORTATION

An overview of the transport distances and transport equipment used in the analyses:

DUCTILE CAST IRON

TRANSPORTATION OF RAW MATERIAL		TRANSPORTATION OF PIPES	
Trailer (diesel)	ca 150km	Car (diesel)	1 300km
Train (electricity)	ca 150km		

GRP

TRANSPORTATION OF RAW MATERIAL		TRANSPORTATION OF PIPES	
Truck (diesel)	1 300km	Car (diesel)	1 270km
Ship (oil)	5,000km		

PE

TRANSPORTATION OF RAW MATERIAL		TRANSPORTATION OF PIPES	
Bulk vehicle (diesel)	110km	Bulk vehicle (diesel)	350km

PVC

TRANSPORTATION OF RAW MATERIAL		TRANSPORTATION OF PIPES	
Bulk vehicle (diesel)	380km	Bulk vehicle (diesel)	600km
Ship (oil)	920km		