Environmental impact of the materials used in the Dutch heat transition

MSc Thesis

January, 2018

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Abstract

The Dutch government set two environmental goals by 2050. One of them is being climate neutral and the other one is to have a circular economy. In order to meet both goals in the best environmental conditions, extensive environmental research is required. This thesis is one of these researches and its main focus is on the climate neutral goal by 2050. In this thesis I start by creating a generic model in ArcGIS that will calculate the required materials and their environmental impacts for the implementation of high and low district heat networks and for air-water heat pumps in residential buildings. The model uses national spatial data of buildings, heat networks, and energylabels and combines them with material data that is retrieved from life cycle inventories (LCI) out of life cycle assessment (LCA) papers, material databases, several manuals, technical specifications on websites and own examination. The model is applied to the Merenwijk in Leiden. The model's results show that for the Merenwijk the indirect environmental impact of the materials will reduce the total reduction in the heat pump scenario by approximately 10% and will be covered in the first 2 years of operation. On the material demand side, the model shows that the Netherlands will face problems with the demand for glass and glass wool. The current market for both materials should be intensified by 4 to 5 times in order to meet the expected demand. Glass wool demands will even reach 2% of the current global mineral wool market. In conclusion this thesis provides an addition to current environmental calculations by looking at the material environmental impact in the Dutch heat transition. The environmental impact of materials does have a significant impact on the overall environmental calculations.

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1. Introduction

1.1 Problem discussion

The Dutch government set themselves an ambitious goal to be climate neutral by 2050, in response to the Paris agreement, which they signed together with 194 other countries. In this agreement countries agreed to limit the global heating to a maximum of 2 degrees Celsius (Ros, et al., 2011). That means that within 32 years the CO_2 emissions should be reduced significantly.

In the Netherlands one of the main CO_2 emitters is the heating of residential buildings by natural gas (Ministerie van Economische Zaken, 2016, p. 18). Around 95% of the entire residential building stock is connected to the gas grid and 92% is directly heated by natural gas (ECN, 2016). In other words, only 3% of the residential building stock that is connected to the gas grid uses an alternative heat source. For the buildings that use natural gas as a heat source, the gas is used for three different kinds of purposes, namely for heating the building (75%), heating tap water (20%) and for cooking (5%) (ECN, 2009). So, in order to reach the climate neutral goal of 2050, the Dutch heat technologies must shift from natural gas, towards more sustainable technologies.

A sector where this shift is already noticeable, is in the construction industry. On the first of July 2018, for example, a prohibition was put in place by the Dutch government on the use of natural gas by architects and constructors in their projects (Didde, 2018). This prohibition forces them to implement more sustainable technologies, like heat pumps and induction hobs in order to make the buildings climate neutral. Additionally, the European Union stimulates the energy sustainability in the residential sector, by setting up various initiatives. One of these initiatives is the EPDB directive (European Parliament, 2003). The EPDB directive is set up to achieve a remarkable reduction in the energy consumption in residential buildings by focussing on heating, cooling, ventilation, hot water taps and lighting.

However, it seems that both the Netherlands' and the European Union's focus is centred around the new built buildings rather than the existing building stock. The focus may be caused by the implicated challenges the heat transition in the existing building stock will face during the transition. They not only have to implement a more sustainable technology, but most of these technologies also require changes in the buildings' insulation, ventilation, heat emission systems and their infrastructure. This would take a considerable amount of time, money and materials compared to the additional costs of sustainable technologies in the built buildings. From 1 July 2018 onwards, around the 70 thousand buildings will be added annually to the existing building stock in the Netherlands (CBS, 2018). This is just the tip of the iceberg compared to the existing building stock. Therefore, the focus should be on the renovation of the existing building stock in order to comply with the requirements for the more sustainable heat technologies and implement them in order to reach the climate neutral goal (Natarajan & Levermore, 2007; Priemus, 2005; Yücel, 2013).

This transition is already gaining notice with some municipalities and they are starting to make plans for a future without natural gas. However, in these plans the main driving forces are time and money, rather than the environment. One of these municipalities is the municipality of Leiden. They created *De Warmtevisie* (2017) in collaboration with Overmorgen, where they suggest 5 alternatives to the natural gas heat network: Renewable gas, biomass boiler, high temperature district heating (HTDH), low temperature district heating (LTDH) and low temperature heating by a heat pump. For each district they suggest the best alternative based on the variables: building age, building type, energy demand, costs (Appendix 5: Interview Overmorgen). What the municipality of Leiden and other municipalities are focussing on in their plans, is to make the transition fast and easy, rather than keeping the main reason for the climate neutral goal in mind and focus on the environmental aspects of the heat transition.

One of these environmental aspects that is missing and often underexposed is the environmental impact of materials. The extraction and processing of raw materials already has an impact on the environment, resulting in things like acidification, climate change, eutrophication, freshwater toxicity, human toxicity, photochemical oxidation, stratospheric ozone depletion and terrestrial ecotoxicity. In the Dutch heat transition the material demand and the material impact on the environment cannot be overlooked. Not only the technology must be replaced, but in some cases, buildings must also be upgraded in order to comply with the heat technology requirements. All these steps will have a significant impact on the material demand and its underlying and underexposed environmental impact and might result in material scarcity, unintended environmental impacts and a dependency on foreign regions.

In order to lower the future demand for virgin materials, the environmental impacts of materials and their dependency on foreign regions, the Dutch government set another goal: The Netherlands circular by 2050. That means that the Netherlands will create an economy by 2050, where waste is not considered lost, but is seen as a resource. They will endeavour to generate as little waste as possible (Het ministerie van Infrastructuur en Milieu & het ministerie van Economische Zaken, 2016). However, the use of materials inevitably generates emissions and other environmental effects across the entire lifecycle. In the linear economy we are living right now, resource demand is increasing, especially for virgin materials (van Exter, Bosch, Schipper, & El Hailouch, 2018). The extraction of virgin materials is an energy intensive process, that is not beneficial to meet the goal of becoming circular by 2050. Another way of extracting materials is by extracting materials from products, that have already reached their end of life. The materials could then be reused or recycled. In this way the environmental impact of the materials will be reduced, the demand for virgin materials will be reduced and the dependency on other geographical locations will be reduced, because the life cycle of the material will be extended (van der Voet, et al., 2017). The difference in energy demand between extracting virgin aluminium and recycled aluminium is a great example of the opportunities a circular economy could offer. The primary production of aluminium costs around 186 MJ/kg, while the energy consumed by recycling costs around 10-15 MJ/kg (Gaustad, Olivetti, & Kirchain, 2012). However, the calculations on the recovery value and recycling rate of materials is still in the beginning stages of research and is dependent on multiple variables like geographical location, time and products it is used in. That makes it at this moment impossible to determine, which material out of which products could be reused or recycled (Oliver-Solà, Gabarrell, & Rieradevall, 2009b).

A paper that acknowledge the lack of detailed material data, is the PUMA paper (van der Voet, et al., 2017). In the PUMA paper, van der Voet explores the copper and aluminium urban mine of Amsterdam by using GIS and material data. Urban mining is a relatively new research topic about the estimation and analysis of material stocks in urban areas in order to mine them at the end of the product’s life (Krook & Baas, 2013). The rough estimations that van der Voet did on the material stock inside the city, might be useful for other projects that can reuse or recycle the explored materials in order to close the loop. In her paper she discovered that there is a large stock of metals present inside Amsterdam. However, the availability is rather slow and will be in small amounts due to the lifespan of appliances they are used in. Besides the appliances there is also a large quantity of metals present in the construction of buildings. However, 95% of the demolition waste is already recycled presently. Therefore, other types of stocks have more potential. A paper that focusses on another type of stock is the paper from Sprecher et al. (2014). They researched recycling potential of the rare earth metal neodymium used in hard disk drives and concluded that the theoretical potential is 57%, while at this moment hardly any neodymium out of hard drives is recycled. Both research projects have the same goal in closing the loop, reducing the material demand and lower the environmental impact of materials used. Combining both papers' themes into a model could give realistic predictions on the future material availability in urban areas. Because of the 2050 goal, the natural gas system will become obsolete and its materials will become available for recycling as they are stripped from existing buildings. In order to make the most use of this recycling potential and in order to reduce the material strain caused by the new heating technologies, a model is needed to combine both the recycling of existing heating technologies and the material costs of their replacements.

The available papers that focus on the sustainable heat technologies in the residential sector, tend to put more focus on energy -requirements, -use and -savings of residentials, rather than the environmental impact of the used materials. They vary from futuristic and still in development technologies like smart thermal grids (Lund, et al., 2014), hydrogen and fuel cell technologies (Dodds, et al., 2015) to the more common and already used technologies and systems like heat pumps (Omer, 2008), heat districts (Sun, Fu, Sun, & Zhang, 2014), solar (Chan, Riffat, & Zhu, 2010) and bio digesters (Wheeler & Segar, 2013). Broadly speaking these papers all focus on the performance and development of the technologies and systems, expressed in energy requirements and do not consider the environmental impact of the materials that are used for these technologies.

The papers that research the materials being used inside sustainable heat technologies and their environmental impacts, also called LCA's, are very limited. The few papers that are available, did their research on just a select group of sustainable heat technologies (Blom, Itard, & Meijer, 2010; Greening & Azapagic, 2012; Oliver-Solà, Gabarrell, & Rieradevall, 2009b; Oliver-Solà, Gabarrell, & Rieradevall, 2009a). In general, these papers focus on one aspect of the heat transition, rather than focussing on the entire process that is needed to reach the 2050 goals. Greening & Azapagic (2012) for example compare environmental impacts of natural gas boilers with three types of heat pumps. They did not only compare the materials used in het technologies, but also included the environmental impact of the operation phase of the technologies and concluded that all the three heat pumps had a higher environmental impact than the natural gas boilers. However, this was mainly caused by the electricity source and the refrigerator used for the heat extraction in heat pumps. A similar paper by Blom et al. (2010), compared just one type of heat pump (air sourced) with the natural gas boiler and came to the same conlcussion as Greening & Azapagic, namely that the elecitricity source and the refrigarator are the main contributers to the environmental impacts of heat pumps.

Papers that focus on the materials of sustainable technologies, and do not include the operation phase, are Oliver-Solà et al. (2009a, 2009b) and Föling et al. (2004, 2005). Oliver-Solà et al. (2009a) focusses on the components and materials when implementing either a natural gas grid or a propane tank. He concluded that for low density areas >1 km pipeline per building, a propane tank is the best environmental option in terms of materials used and their impact on the environment. This is because in low density areas the neighboorhood system has the largest environmental impact, while in the high density areas the dwelling system has the largest impact. The other paper, on the district heat network (2009b), is a similar study that is not focussed on the different subsystems of the natural gas grid, but is focussed on the district heat network, where they conclude that the majority of the environmental impacts is from power plants and the dwelling subsystem. The papers by Föling et al. (2004, 2005) conclude on the other hand that not the dwelling subsystem and power plants would have the most impact, but the excavation done for the pipelines and the steel in the pipelines itself have the most impact. The difference between the research done by Oliver-Solà and Fröling, is that Oliver-Solà focusses more on the different subsystems, including the dwelling subsystem, while Fröling goes more in detail on the actual heat network itself and does not focus on the dwelling subsystem. However, what all these papers have in common, is their focus on the environmental impact of the materials that are used in the heat transition. The difference between them is the scope and focus on parts of the systems. Nonetheless, they still only focuss on specific elements of the heat transition, while the whole heat transition is far more complex. The implementation of low temperature heat systems for example does not only have direct impact on the material demand and environmental impact, but also has an indirect impact by forcing the older buildings to improve their insolation, ventilation and heat emission systems. With the deadline of 2050 coming closer, a thorough analysis of different heating scenarios in the Netherlands is necessary and could provide new insights in the importance of this transition, not only for the technologies, but also for the indirect consequenses of implementing a more sustainable heat technology.

Combining the material inventories from the LCA papers with spatial data of the Netherlands could give interesting insights in the environmental impacts of different heat transition scenarios. Also, combining spatial data containing the measurements and characteristics of the residential buildings, with the material requirements for the heat transition will give a more realistic understanding when compared to previous papers that only focus on one type of building or technology.

In this thesis I focus on the material demand and the environmental impact of the materials used in the heat transition. I do this by combining different inventories from previous LCA studies to create an overview of the amount of materials that are needed and what the impact of these materials are in the Dutch heat transition. Using a combination of LCA and GIS brings relatively new concepts together and results in a spatial overview of spatial and environmental data combined. The aim is to provide a generic spatial model, that is not bound to a geographic location, that runs different scenarios resulting in a spatial overview of the materials that are needed in the heat transition and the impact these materials have on the environment. Unique values per building will be created by using for example the total building area multiplied by the insulation materials that are needed per square meter. To showcase both the power and the restrictions of this model, I will perform a case study on the Merenwijk in Leiden.

1.2 Research questions

1.2.1 Main question

The main question that will be answered throughout my thesis is:

What are the material requirements and environmental impacts of required materials for replacing the gas fuelled boiler by more sustainable alternatives?

1.2.2 Sub questions

To give a clear answer to the main question the following sub questions will be answered:

- How much material is currently contained in the gas fuelled heat system in the Merenwijk?
- How much material is needed to complete the heat transition in the Merenwijk?
- What is the environmental impact of the materials that would be needed for the heat transition?
- How can these estimations be carried out in an automatic way using GIS?

Throughout the thesis different methods are used and combined. In this subsection a brief explanation will be given on the methods used for each research question.

How much material is currently contained in the gas fuelled heat system in the Merenwijk?

To answer this question material data is needed. In this thesis the data that was collected by Oliver-Solà et al. (2009a) is used (Figure 1.3). His data is a material inventory of the gas network and of the adjustments on building and dwelling level per 100 meters of gas network. To this gas network 10 buildings are connected and contain an average of 24 dwellings. In order to use this data for the Merenwijk, the data needs to be adjusted to the characteristics of the Merenwijk. The characteristics that are needed are: the length of the gas network within the Merenwijk (*Gasnet* spatial layer (Figure 1.1)), the total amount of buildings connected to the network (*BAG3D* spatial layer (Figure 1.2)) and the total amount of dwellings (*Adres* spatial layer (Figure 1.2)) in the Merenwijk. The calculations on the spatial layers are done in ArcGIS and the actual material inventory is made in Excel (Figure 1.4). The whole process is visualised in Figure 1.

Material	Kg/dwelling
Brass	18
Bronze	5.27
Cardboard	0.93
Cast iron	17.62
Cement	244.41
Ceramic brick	170.08
Concrete	304.95
Copper	58.22
Galvanized steel	12.38
Glass fiber	10.3
HDPE	38.87
Limestone	12.88
Plastic	0.00049
Priming	2.02
PVC	8.02
Sand	4028.20
Stainless steel	8.4
Steel	18.90
Synthetic rubber	0.06
Wood	0.04

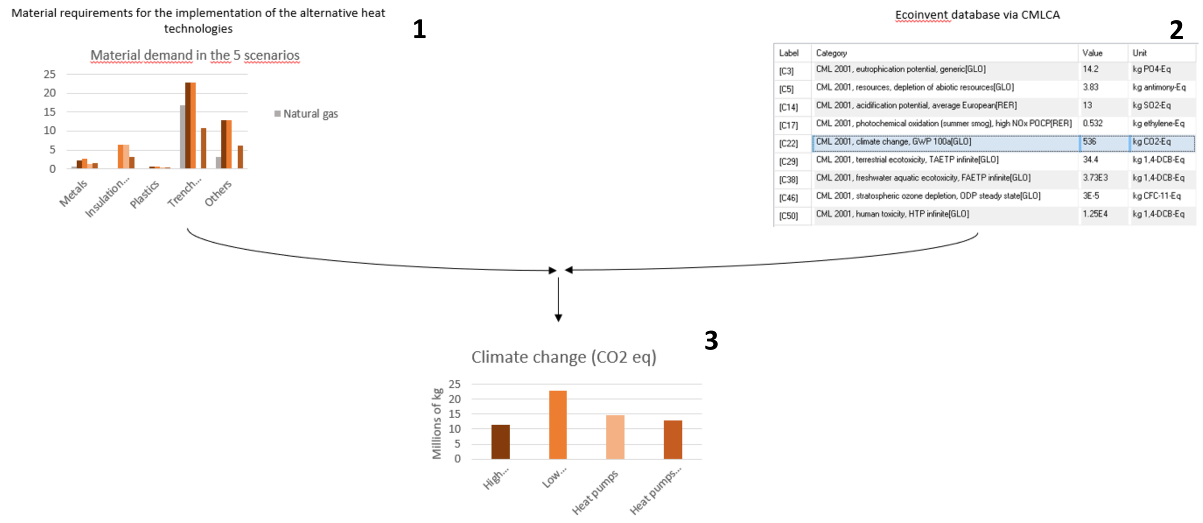
Figure 1 Combination of data sources to make a material inventory of the current natural gas heat system in the Merenwijk (1) Spatial layer of the natural gas pipelines in the Merenwijk, (2) Spatial layer of the residential buildings in the Merenwijk, (3) Life cycle inventory of Oliver-Solà et al. (2009a), (4) Material inventory of the current natural gas pipelines and natural gas hob in the Merenwijk (Supplementary excel file: 'Technologies'

How much material is needed to complete the heat transition in the Merenwijk?

To answer this question the same steps are used as in the previous question. So, by finding available material data, suitable spatial layers and by performing calculations on a combination of both. In this thesis, there are three alternative heat technologies considered (heat pumps, low temperature district heating and high temperature district heating), each having their own data. The high temperature heat network calculation is comparable to the gas network calculation, while the low temperature alternatives are more extensive and dynamic. For the low temperature alternative technologies not only the heat technology must change, but also the insulation, ventilation and heat emission systems will have to change. To get a better understanding of the different impacts of the three different heat alternatives four different scenarios are made: all high temperature district heating, all low temperature district heating, all heat pumps and half hat pumps/half high temperature district heating.

What is the environmental impact of the materials that would be needed for the heat transition?

For this research question I need the total amount of materials that is needed for the heat transition and the environmental impact of each individual material. A model for the total amount of materials is already created to answer the previous question. The environmental impact of each material is extracted from the ecoinvent 3.4 database via the CMLCA software tool. The ecoinvent database is an enormous database that contains environmental impact data of a significant amount of materials and processes. Since total amount of materials that were needed for each scenario is already known (Figure 2.1), the environmental impact per kilogram of these materials could be calculated in CMLCA (Figure 2.2). Multiplying the total amount of required materials by the environmental impact per kilogram of material will lead to the environmental impact of the materials used in the heat transition. There must be said that this is calculated from cradle to market and does not contain the entire lifecycle of the materials. The entire process explained in this paragraph can be seen in Figure 2.



Label	Category	Value	Unit
[C3]	CML 2001, eutrophication potential, generic[GLO]	14.2	kg PO4-Eq
[C5]	CML 2001, resources, depletion of abiotic resources[GLO]	3.83	kg antimony-Eq
[C14]	CML 2001, acidification potential, average European[RER]	13	kg SO2-Eq
[C17]	CML 2001, photochemical oxidation (summer smog), high NOx POCP[RER]	0.532	kg ethylene-Eq
[C22]	CML 2001, climate change, GWP 100a[GLO]	536	kg CO2-Eq
[C29]	CML 2001, terrestrial ecotoxicity, TAETP infinite[GLO]	34.4	kg 1,4-DCB-Eq
[C38]	CML 2001, freshwater aquatic ecotoxicity, FAETP infinite[GLO]	3.73E3	kg 1,4-DCB-Eq
[C46]	CML 2001, stratospheric ozone depletion, ODP steady state[GLO]	3E-5	kg CFC-11-Eq
[C50]	CML 2001, human toxicity, HTP infinite[GLO]	1.25E4	kg 1,4-DCB-Eq

Figure 2 Combination of material inventory made for the different scenarios in the heat transition (1) and the environmental impact of the materials per kilogram of the material from ecoinvent 3.4 (2). The multiplication of them both results in different environmental impact categories per scenario (3).

How can these estimations be carried out in an automatic way using GIS?

The answer to this question is intertwined with the explanations of previous questions and can be found throughout this thesis. To make the estimations automatic, first I made a generic model. This means that all the system boundaries that are set are not considered by setting up the model, but would be implemented later in to model. In order to create such a model, the following was required: the model builder tool of ArcGIS, spatial data of the Netherlands, assumptions and estimations on the characteristics of the buildings, and generic material and environmental impact data. An overview of the model inside the model builder can be seen in Figure 3.

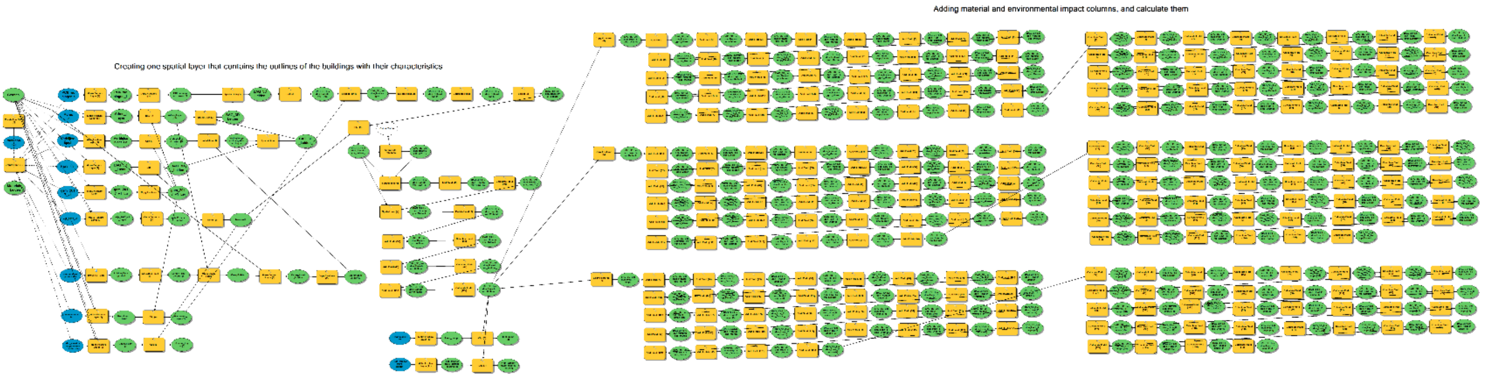


Figure 3 Generic model built in the model builder of ArcGIS. Explanations for all the steps that are made can be found in Appendix 2.

1.3 Case study area the Merenwijk

The Merenwijk is one of the ten districts in the municipality of Leiden and has approximately 14.500 citizens. It is an average district with 10% of the total citizens that are housed in Leiden. The amount and diversity of buildings inside the Merenwijk can be seen in Figure 4.

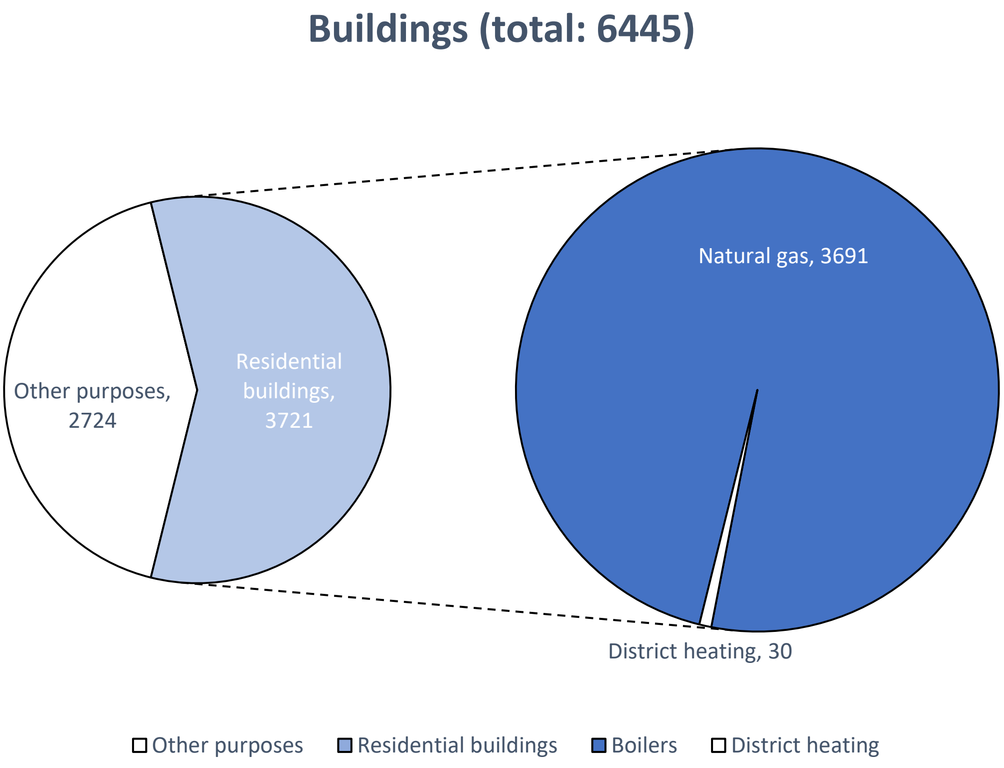


Figure 4 Building composition within the Merenwijk with the focus on the residential buildings

This research is interested in the residential buildings that are heated by natural gas. Sixty percent of the buildings in the Merenwijk are residential buildings, 99% of those are heated by natural gas. This means that almost the whole residential stock inside the Merenwijk needs to replace their heat technology with a more sustainable alternative. The impact of the replacement on the buildings itself and the environment is not only dependent on the selected alternative, but also on some of the characteristics of the building. One of the most important characteristics of a building is the construction year. This characteristic can give a good indication on how the building is heated, ventilated and insulated. In Figure 5 the construction years of the residential buildings in the Merenwijk are presented. The most common period is the period from 1975 -1982, followed by 1965-1974 and a few buildings in the periods after 1983. This means that the insulation, ventilation and emission system in the residential buildings of the Merenwijk are outdated and will most likely have to be replaced during the heat transition.

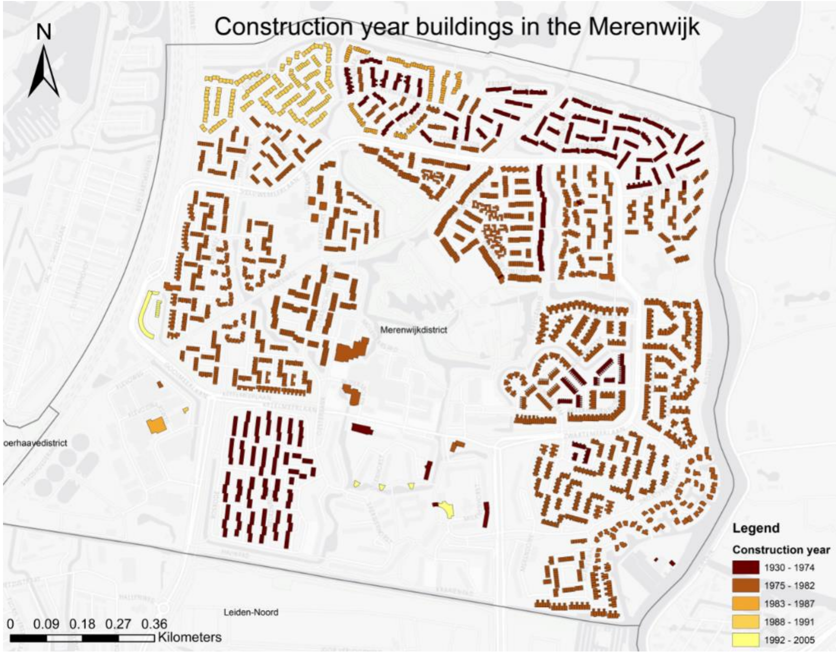


Figure 5 The *construction year periods of the residential buildings that are heated by natural gas in the Merenwijk*

1.4 Thesis overview

The next chapter, chapter 2, the background research on the current gas network in the Netherlands and the more sustainable alternative heat technologies are presented. In the end of this background research scenarios are chosen that might not be the most realistic, but are made to get a better understanding on the impact of the different heat alternatives. The four scenarios will be used throughout the thesis as a technological boundary. In chapter 3 the general methods used, GIS and LCA, are explained and the system boundaries are given. The description and calculation of the material inventory can be found in chapter 4. Chapter 5 continues with the results of the material inventory calculations and the environmental impact calculations per scenario. In the end of the chapter, the model is also tested on a larger research area (Leiden) and these results are presented in 5.4. For the model several input parameters are used. To test the impact of changes in input data on the results, a sensitivity analysis is provided in chapter 6. After that chapter, the thesis results will be discussed, concluded and recommendations will be given for further research in the discussion, chapter 7.

2. Background research

2.1 Natural gas heat technology

In the Netherlands 95% of the households (Hier, 2018) are connected to the gas grid and most are dependent on natural gas as heat source. Switching to another technology will make the gas network redundant. With a physical and economical lifespan of 50 years the gas network will be a major challenge for the grid operators like Liander to deal with. The average lifespan of gas pipelines is 40 to 50 years. So, every 40 to 50 years the gas pipelines get renewed. At this moment this is still an ongoing process and the new pipelines have a lifespan that exceeds the 2050 goal. It is most likely that the pipelines will not be dug out the ground before their lifespan is over, because more than 70% of the total costs are digging costs (DNV KEMA Energy & Sustainability, 2013). Therefore, the pipelines will be considered in this thesis as a hibernating stock. The other parts of the network, like the boilers and gas hobs will get replaced by more sustainable solutions. The replaced boilers and gas hobs have four possible treatments: land fill, incineration plant, recycling facility or getting reused. The last option would be the most ideal option, but is also the most unlikely option since the Paris agreement is signed by 194 other countries and not all countries use natural gas in the residential sector.

2.2 Renewable heat technologies

In *De Leidse Warmtevisie* there are five alternatives mentioned to replace the natural gas fuelled systems:

1. Renewable gas
2. Biomass boiler
3. High temperature district heating
4. Low temperature district heating
5. Low temperature heating with a heat pump

The five technologies in the *Warmtevisie* are chosen in this thesis based on the current state of the heat technologies. In the next five sub headers I will explain what the technologies are, what their purpose is, what their positive and negative characteristics are, what their applicability to Leiden is and lastly I will select the technologies that will be used in the model.

2.2.1 Renewable gas

Renewable gas is a biogas which has the same quality as the natural gas that is used in the current system. Therefore, using renewable gas as an alternative does not need many adjustments to the current buildings, since the quality of the gas before and after the transition remains the same. The Netherlands can only supply a limited amount of renewable gas. Therefore, this solution will not be feasible on a large scale and would be a better solution for historical/monumental buildings, that are not only hard to insulate due to restrictions, but are also hard to reach trough the complex underground (Gemeente Leiden, 2017). However, it may not be as ideal as it seems, because the costs of maintaining the network for such a small number of residents will increase as more people disconnect from the network. Given this small implementation scale, the increasing costs and the available alternatives, renewable gas will not be considered in this model.

2.2.2 Biomass boiler

Another alternative, also for the buildings that are more difficult to adjust, are the biomass boilers. These boilers use biomass as fuel. The most common biomass boiler for residential purposes are pellet stoves. These stoves use wooden pellets as fuel to heat the buildings. In Leiden there is not much wood available to heat the buildings. A rough estimation is that a few hundred buildings can be heated using wood. This makes it an even smaller scale solution than the renewable gas alternative, if import is not considered. Another side effect of the biomass boilers is the increased particle emissions, majorly dominated by fly ash, that would not do any good in urban areas as well (Sippula, Hytönen, Tissari, Raunemaa, & Jokiniemi, 2007). There are however filters on the market that could reduce the amount of fly ash, but that would economically not be meaningful on building level (Obernberger, Brunner, Mandl, Kerchblaum, & Svetlik, 2017). Therefore, also the biomass boilers will not be considered in this thesis.

2.2.3 High temperature district heating (HTDH)

High temperature district heating is a network of pipelines filled with water that is heated by, for example, waste heat from industries, green gas or geothermal pumps. The outgoing temperature of high temperature district heating has a minimum of 70 degrees Celsius and returns at 40 degrees Celsius. The benefits of high temperature district heating are that it is applicable on a large scale and the water for heating will be the same temperature as in the natural gas situation. That means not many changes are needed inside the natural gas heated residential building to switch to the more renewable alternative of high temperature district heating.

However, labelling the network as renewable is a point of discussion. High temperature heating is an inefficient way of heating residential buildings, where a significant amount of heat gets lost. Also, using fossil fuelled industries as a source of heat, is mitigating the environmental impact of a fossil fuelled process, but still stimulates the use of it. Using it as a renewable source will therefore cause a locked-in effect, where the network is dependent on fossil fuels. Economically speaking the return on investment period is rather large and high investments costs are needed (Colmenar-Santos, Borge-Diez, & Rosales-Asensio, 2017). In this large period alternative heat technologies can be developed and improved and can become more advanced and sustainable, than the high temperature heat network. With the large amount of buildings that need to be connected to the high temperature network, a large amount of buildings will be locked in. However, it can also be that industries nevertheless continue to produce the heat and that reusing the waste heat is a way of closing the loop.

Leiden already has a relatively large developed district heat network (Figure 6) that is depended on the waste heat of the EON factory. The factory is however closing and from 2020 onwards the municipality of Leiden will collaborate with the harbour of Rotterdam to use their waste heat. This is all part of a bigger plan*: de Warmterotonde*, where several major cities around Rotterdam will be connected by pipelines that go from the harbour of Rotterdam in a roundabout through several cities. This is a good example of a system where locked-in takes place. The buildings of several major cities are dependent on a fossil fuelled system. However, the benefit of this system are the relatively small material requirements and the large scale it can be implemented on. There is still a debate ongoing on whether Leiden should expand the heat network or should only use the network that is already available. Because expanding the network would mean less heat will be unused in the industries of Rotterdam, but it will enlarge the number of locked-in buildings. Since the heat network in Leiden is already developed and there is a possibility to expand after 2020, I will take the high temperature district heating into account into the model as an alternative for natural gas.

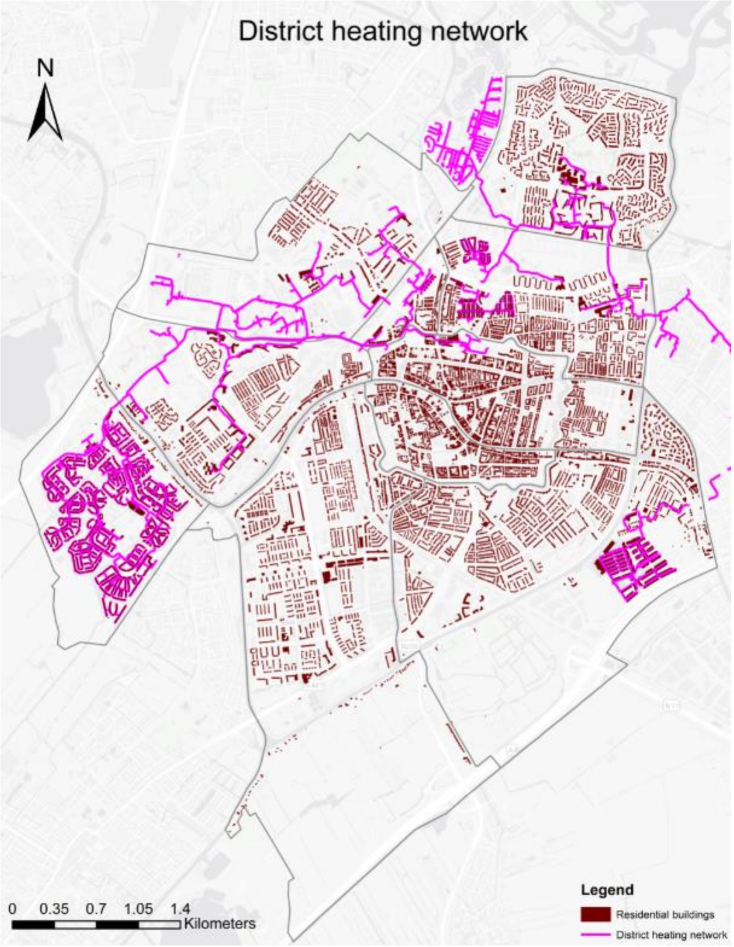


Figure 6 The district heat network in Leiden

2.2.4 Low temperature district heating (LTDH)

Low temperature district heating is the same kind of heat technology as the high temperature district heating, except for the water temperature and the possible heat sources. The low temperature district heating has a maximum temperature of 55 degrees Celsius, where the high temperature network has a minimum of 70 degrees. Because of the lower temperature the loss in heat transport is also limited. The main heat sources for the low temperature heat network are geothermal heat pumps, the backflow from the high temperature network, biomass plants and surface water.

In the network itself the low temperature is more energy efficient than the high temperature network. But looking inside the residential buildings major changes must be made to make the low temperature heat work a comfortable source of heating for the residents. The main changes are in insulation, ventilation and heat emission systems. In the existing building stock there are already insulation, ventilation and heat emission systems present. The quality of this will depend on the year of construction and the upgrades that happened over time. In the end all buildings that will be connected to a low temperature network needs to be upgraded to a standard where temperatures between 30-55 degrees Celsius are enough to comfortably heat the houses. That means that glass need to be upgraded to HR ++ glass, but also the floors, roofs and walls need to be upgraded. Better insulated buildings also mean that better ventilation is needed to keep the oxygen level comfortable. This whole process of insulating, ventilating and heating will be material intensive compared to the high temperature network.

The heat emission system in the already constructed buildings mostly consist of high temperature radiators that are not capable to heat the well-insulated buildings with low temperature heat. These radiators need to be replaced by low temperature radiators or additional technologies like radiator fans or underfloor/wall heating are needed. The radiator fan is a small device that can be put on an existing high temperature radiator to make it suitable for low temperature heat. It would be ideal for situations where new high temperature radiators have been placed recently. Underfloor heating on the other hand seems to be a drastic and intensive operation to perform in an already built building, but when it will take place, ideally it will be combined with floor insulation to lower the cost and optimize the process.

Low temperature district heating seems to be material intensive, especially compared to the high temperature district heating. However, the benefit of low temperature heating is the energy savings due to the insulation and the more sustainable fuel sources. Comparing the savings in environmental impact between the fuel sources and the materials will give interesting insights in the sustainability performance of both technologies and therefore low temperature district heating is also used in this thesis as an alternative.

2.2.5 Low temperature heating with a heat pump

Another system that can replace the natural gas system is the heat pump system. A heat pump is a device that transfers heat from one source to another. In my thesis I will focus on the low temperature heat pumps, because the low temperature heat pumps are already regularly used as alternative and the high temperature heat pumps are rarely used due to their inefficiency. The low temperature heat pumps know three different heat sources: Geothermal-, air- and water sources. For each kind of source there are several types of heat pumps. Air heat pumps have for example air-water heat pumps and air-air heat pumps. The air-water means that heat is extracted from air and put into the water. This water is then spread all over the building by pipelines, the same as in the natural gas fuelled system. However, just replacing the natural gas boiler by an air to water heat pump is not possible. The produced low temperature heat in the heat pumps is far lower than the high temperature heat form natural gas boilers. Therefore buildings, as in the low temperature heat network, need an upgrade in their insulation, ventilation and heat emission systems.

In the *Warmtevisie*, Leiden mentioned two types of heat pumps as replacements for the natural gas boilers: geothermal and air heat pumps. Both heat pumps mentioned are low temperature heat pumps. In my thesis I will focus on the last one, the air heat pumps and to be more specific: the air-water heat pump. This heat pump can be used on a large scale as it fits in all types of buildings. The downside of this low temperature heat pump is that most buildings in the Merenwijk will need improved insulation, ventilation and alternatives for existing radiators. But since all low temperature heat pumps need these improvements it is not considered as a downside when comparing different types of heat pumps. All other types of heat pumps are left out. The geothermal source heat pumps are left out because they are too expensive, complicated to implement and because their effect on the soil and the heat balance underground is still uncertain. The water source heat pumps are left out for the same reasons and additionally for the interaction with groundwater which is strictly regulated, so this will cost a lot of effort and money to accomplish at this moment.

2.3 Insulation, ventilation and heat emission systems

As already explained in 2.2 when implementing low temperature heat technologies as an alternative for natural gas a lot must change inside the building itself besides the heat technology itself. There is a need for change in insulation, ventilation and heat emission systems. For insulation there are different types of surfaces that could be insulated, different methods per type of surface and different materials that can be used. For ventilation there are different ways of ventilating a building: natural, mechanical or heat recovering ventilation. For heat emission systems there are options in different types radiators and peripherals: high temperature radiators, low temperature radiators or radiator fans. All these insulation, ventilation and emission system options can be split into two groups: A normal group, where the goal of 2050 is met with the most common operations, and an ambitious group, where insulation, ventilation and the heat emissions systems are performing in the most sustainable way. This ambitious goal goes hand in hand with high costs, major operations inside the buildings and high material demand. Therefore, in this thesis I will focus on the normal group with the most commonly used procedures.

2.3.1 Insulation

The type and quantity of insulation inside the buildings depends on their construction year (Table 1), but also on the upgrades since then. The upgrades that have been installed, will be measured later by connecting the energy label to the construction year of the building.

Before 1930 there were just walls with no cavities and insulation. After 1930 the cavity walls appeared inside buildings, but were still empty without any insulation material. From 1975 onwards, insulation materials appeared inside the cavity walls and the insulation value (Rc) increased. For the floor, roof and walls there was not much regulation before 1965 on the insulation values. Only after 1965 additional requirements were set by the government on these values (Liebregts & Persoon, 2011; Bouwbesluit 2012; Appendix woonwijzerwinkel).

Construction	**1965**	**1975**	**1979**	**1982**	**1987**	**1990**	**1992**
Floor	0.17	0.26	0.52	1.3	1.3	1.3	2.5
Roof	0.86	1.03	1.29	1.3	2	2.5	2.5
Wall	0.43	0.69	1.29	1.3	2	2.5	2.5

Table 1 Minimal insulation value (Rc) requirements given by the Dutch government per construction year period (Liebregts & Persoon, 2011)

The insulation materials that are commonly used in the construction sector are the mineral wools like glass- and stone wool and PUR foam. These insulation materials are commonly used because they are easy to implement, relatively cheap and have a low impact on the environment. There are plenty of other insulation materials around as well, but they are mostly small-scale solutions that are not applicable to the scale we are looking at. In this thesis glass wool will be used as insulation material for the floor, roof and wall. Glass wool is chosen because it is a regular used insulation material in the construction sector and one of the best performing in terms of environmental impact (Nibe, n.d.).

2.3.2 Glass

The type of glass that is present in the buildings also depends on the construction year. Buildings that are older than 1974 have single glass windows. Buildings that are built between 1975 and 1982 still have mostly single glass, except for some living rooms. Buildings after 1982 mostly have double glass in all their windows. All buildings after 2005 most likely have HR++ glass or triple glass. That means that for all buildings that are older than 2005 the windows need to be replaced. Triple glass (HR+++) is the best insulating glass with an insulating gas in between the three panes. It also requires the most amount of glass. Another option to reach the insulation requirements for the low temperature alternatives, is the use of HR++ glass. This is double glass with argon gas in between. In this thesis HR ++ glass will be chosen, because of the reduced material demand compared to HR+++ glass.

2.3.3 Air vents

The downside of very good insulation is that air circulation between the inside and outside of the home is restricted. In order to provide enough oxygen to live, additional ventilation must be installed. One way to do that is by natural supply and mechanical discharge. The natural supply of air can be facilitated by air vents. Air vents are small vents that can be placed in the window frames or above the glass. Because all buildings need to replace their glass by HR++ glass the air vents will be placed above the glass. In this thesis the air vent will be the DucoTop 50 ‘ZR’ (DucoTop 50 'ZR', n.d.). This is an air vent that is already on the Dutch market, is easy to implement, can be put above the glass and is relatively small.

The requirements for the amount of ventilation that is needed inside residential buildings are set in *het bouwbesluit* (2012). Residential buildings have different rooms: lounges, toilet rooms, bathrooms, technical rooms and storage rooms, that can be split into groups: residential areas and other areas. The residential areas (living room, bed room and kitchen/dining room) in dwellings are at least 55% of the total dwelling area and their ventilation capacity must be at least 6 $dm^3/s/m^2$ (Bouwbesluit 2012). In the other areas (45%) the supply of fresh air is provided by chinks under the doors to let the air flow from one room to another and no additional ventilation is needed. That means that in the living room, bed room and kitchen/dining room air vents need to be placed that meet the ventilation requirements for the total area of the residential building. In the buildings before 2005, there are hardly any air vents present. Because most buildings in the Merenwijk were built before 2005, the assumption is made that there are currently no air vents present in any building in the Merenwijk.

2.3.4 Mechanical ventilation

In residential buildings built before 1983 most of the ventilation was natural ventilation. That means that both the supply as the discharge of air was regulated in a natural way. Residential buildings after 1983 became more insulated and needed mechanical ventilation to get the dirty air out of the building. These buildings are already suitable for low temperature heating, when it comes to discharge air. In the buildings before 1983, that are not renovated yet, the natural ventilation needs be replaced by installing a mechanical ventilation unit on the old ducts or a heat recovery ventilation. The heat recovery ventilation is a ventilation system where heat from the inside air is extracted and is passed on to the inflowing air. This is an energy efficient process for heating and ventilating buildings. However, it got some practical downsides compared to a mechanical ventilation unit: it costs significantly more, it is significantly larger unit, several adjustments have to be made inside the house, it has to be well maintained by the residents and it requires more materials to build and implement. For these reasons this thesis will look at the replacements of natural ventilation by the mechanical ventilation in buildings before 1983.

2.3.5 Heat emission systems

In all the construction year periods that are considered in this model the buildings are heated by conventional radiators. These radiators perform best with high temperature water as fuel. Replacing this high temperature fuel will reduce the efficiency and capability of getting the room at a comfortable temperature. However, it is questionable if all radiators need to be replaced or need an extra radiator fan. Research in this field is developing, but lacking at this point. In this model all conventional radiators will be supplied with a radiator fan to increase the efficiency and speed of heating the building to a comfortable level. Another option would have been to implement the low temperature radiators. However, since the renovation of buildings is already a material intensive process, the relatively small adjustments for the implementation of radiator fans is a more suitable option.

2.4 Induction hob

Replacing natural gas by more sustainable heating sources will also have an impact on the way people cook. In most residential buildings in the Netherlands people still cook on natural gas hobs. Disconnecting from natural gas will also force people to look for alternative cook systems. The two most used alternatives are cooking on electric and on induction hobs. The benefit of induction cooking over electric cooking is that cookware is directly heated by magnetic energy. This is far more efficient than heating the cookware indirectly by electricity or gas. The downside however is that all pans need to be replaced in order to use the magnetic energy. In my thesis model I will assume that, even though people have to replace their pans, people use the induction alternative over the electric alternative.

2.5 Scenarios

In this thesis four different scenarios are considered to compare the three different technologies with each other:

- All high temperature district heating
- All low temperature district heating
- All heat pumps
- Half heat pumps/ half high temperature district heating

One of the four scenarios is the most likely scenario for the Merenwijk, where around 50% of the dwellings will have heat pumps and the other 50% will be connected to the high temperature district network. In the other three scenarios the Merenwijk will be connected to one of the alternative technologies for the full 100%. These three scenarios will be used to make a comparison between the material impact of the different heating technologies. The environmental impacts of the required materials will be based on the scope that will be described in 4.10.

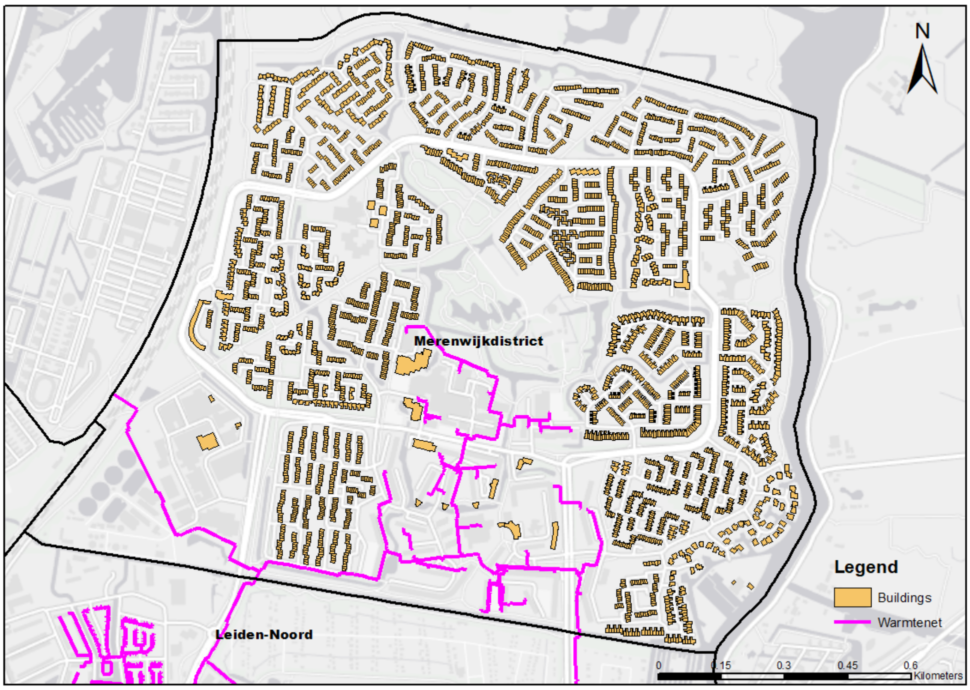
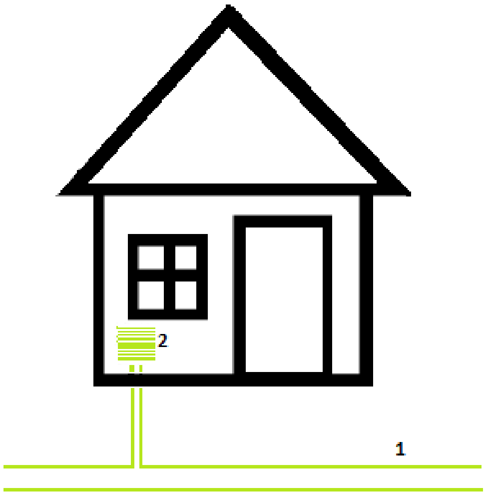


Figure 7 Current district heat network in the Merenwijk and the residential buildings that are connected to the natural gas grid

2.5.1 All high temperature district heating

When the district heating capacity can be expanded significantly in Leiden, they may choose for a scenario where all buildings will be connected to the district heat network. The heat originating from the *warmterotonde* is high temperature heat. Using this as source for the whole district will result in an inefficient use of energy. However, the dwellings do not need additional insulation, which leads to a lower material impact per dwelling. The only change that must be made is the implementation of the heat network and the heat exchangers inside the dwellings as can be seen in Figure 8.



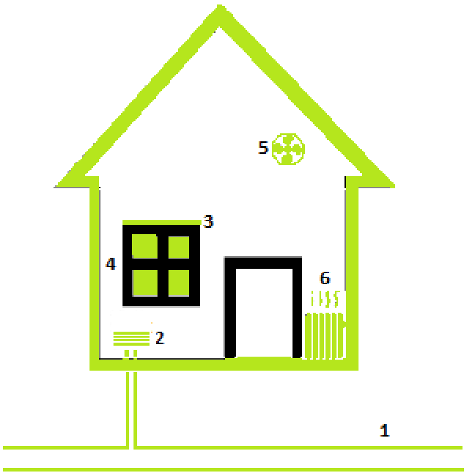
1 District heat network

2 Heat exchanger

Figure 8 Adjustments for implementing high temperature district heat network

2.5.2 All low temperature district heating

In this scenario all dwellings will be connected to a low temperature district heat network. This can be a result of improving the insulation of the residential buildings significantly, while being connected to a high temperature district heat network. Because of the better insulation the heat in the high temperature network is set to low temperature. However, the adjustments that are needed to transit the high temperature to low temperature is quite a challenge. The heat exchanger must be made smaller and the pressure or the size of the pipelines must be changed in order deliver the lower energy demand. However, the main difference in materials is for the improved insulation, ventilation and heat emission systems (Figure 9). There could also be a difference in materials when the transition is from natural gas boilers to low temperature district heat network. In this scenario no metal pipes are used, as in the high temperature scenario, but plastic district heat pipes can be used (Schmidt, et al., 2017).



1 District heat network

2 Heat exchanger

3 Air vent

4 HR ++ glass

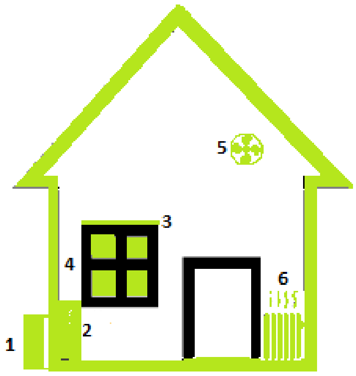
5 Mechanical ventilation

6 Radiator ventilator

Figure 9 Adjustments for implementing low temperature district heat network

2.5.3 All heat pumps

In this scenario all natural gas will be replaced by air-water heat pumps. This might happen when the extra district heating capacity will not be delivered or is not available for the Merenwijk due to other priorities. The *warmterotonde*, the project behind the 2020 contract, and its capacity per city and district is not known yet and can result in a scenario where district heating is not an option. Implementing heat pumps in all dwellings will create a decentralized network where each dwelling will have its own network and technology. The downside compared to the high temperature district heating is that every building need improved insulation in order to make the heating by heat pumps comfortable and efficient. This means increased materials and increased material impact, but a more efficient use of heat. All adjustments that need to be made can be seen in Figure 10.



1 Outside unit air-water heat pump

2 Inside unit

3 Air vent

4 HR ++ glass

5 Mechanical ventilation

6 Radiator ventilator

Figure 10 Adjustments for implementing heat pumps

2.5.4 Half heat pumps/ Half high temperature district heating

In this scenario both the heat pumps and high temperature district heat network will be combined. In the lower part of the Merenwijk there is already district heating present (Figure 7) and has a higher change of being expanded than the northern part of the Merenwijk where no district heating is present. At this moment the district heat network has reached its capacity in delivering heat to dwellings. From 2020 onwards, a new contract is signed with the industrial area of Rotterdam. This new contract contains an increase in heat capacity. This means that there will be room for network expansion in Leiden (Appendix 5: Interview Nuon). In Figure 11 I created the possible scenario based on the current network and the possibility to expand to nearby neighbourhoods. The high temperature network in this scenario can in the future be changed to a low temperature network, when insulation will be improved and when it would be beneficial to do so.

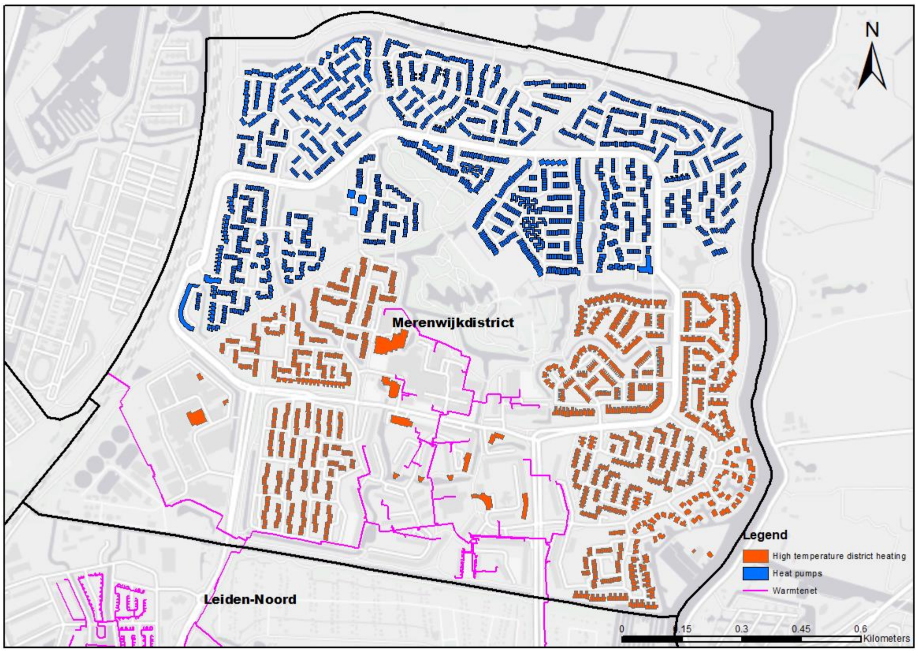


Figure 11 Combination of heat pump and district heating scenario

3. Methods

3.1 System boundaries

The model that is used throughout the thesis is defined by several boundaries in order to create useful and clear results. The geographical boundary of the model is the Merenwijk district of Leiden. The technological boundaries are based on the *Leidse Warmtevisie*, their implementation scale and proven merit. The boundaries are set to the original natural gas system and three sustainable alternatives: low temperature district heating, high temperature district heating and low temperature air-water heat pumps. The boundaries for future vision are set to 4 scenarios: All high temperature district heating, all low temperature district heating, all heat pumps and half heat pumps/ half high temperature district heating. Lastly, presentation of material data in the maps will be done on building level.

3.2 GIS

To create a model that could not only combine different datasets, but could also create maps, ArcGIS 10.2.2 is used. It is used to efficiently capture, store, update, manipulate, analyse and display all forms of spatial data (Redlands, 1990). To work with the spatial data, the geographic approach was used. This is a five-step approach (Figure 12) intended to help structure studies that use spatial data in combination with GIS. The structure provides a research focused basis to deal with the different kinds of datasets that were acquired during the thesis and helped in structuring the various datasets in order to implement them into the GIS model.

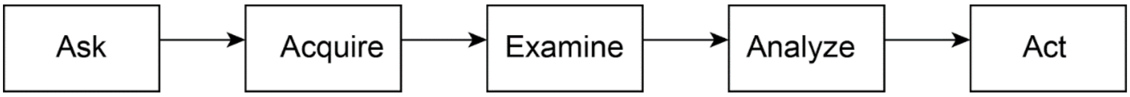


Figure 12 The five steps of geographic approach (Artz & Baumann, 2009)

The GIS framework used in the thesis uses the heat transition vision of the municipality of Leiden and is based on already existing models: the Overmorgen model (Overmorgen, n.d.) and the PUMA model (van der Voet, et al., 2017). In this thesis both model subjects were combined to create a model that calculates the material requirements and environmental impact of the different heat transition scenarios in the residential sector. This model was built in the Model builder tool of ArcGIS and is generic. That means that it can run and be adjusted on any computer having ArcGIS and the referred data layers of Table 2. The main layer of the model is the BAG_3D layer. This layer contains the outlines of every building together with the total surface area and building height. The calculations on materials and their environmental impact were calculated with the field calculator tool, supported by excel sheets on the materials that are used for implementing low and high temperature technologies. With these calculations inside the GIS model I could create maps and graphs of the different heat transition scenarios.

Data set	Data layer	Year	Source	Link
BAG_3D	BAG_3D	2017	Maarten van 't Zelfde	https://surfdrive.surf.nl/files/index.php/s/lyygPF4aiZ90rwX
CBS_Wijk-_en_Buurtkaart_2017_v1	gem_2017_v1	2017	CBS	https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische%20data/wijk-en-buurtkaart-2017
	wijk_2017_v1			
BAG	Verblijfsobject_v	2015	Nederlandse overheid	https://data.overheid.nl/data/dataset/basisregistratie-adressen-en-gebouwen--bag-
	Adres			
Kaartlagen Energieatlas	PC6_woningen.shp	2014	NGR	http://www.nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/24bb1d2b-a236-45ee-ab60-90143bc152d2
Energielabel	EPBD_1_april_2018_ontdubbeld_woningen	2018	RVO (Marja Peperkamp)	
Warmtenet	Warmtenet.shp	2018	Gemeente Leiden (Johan Glasbergen)	
Gasnet	shp_assetdata_gemeente_Leiden.shp	2018	Liander (Ronald Orlando)	

Table 2 The spatial data layers that are used in this thesis

4. Material inventory description

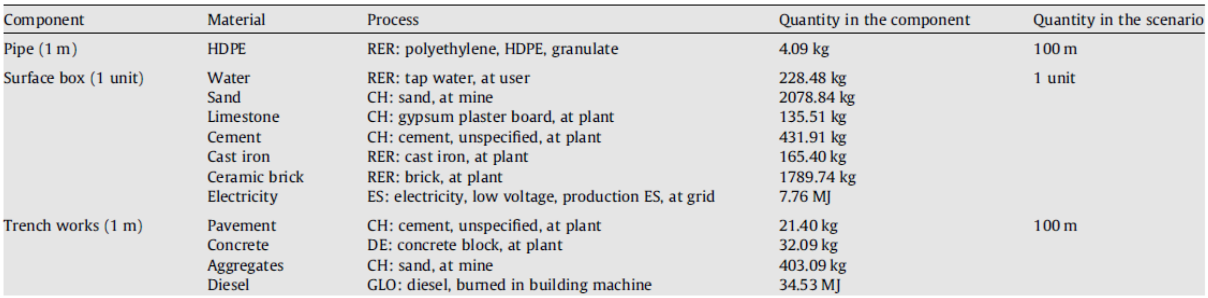
The material inventories, where the material environmental impact calculations depend on, are the main input in the GIS model. The data is gathered from various life cycle inventories (LCI) and life cycle assessment (LCA) papers, the database Nibe, several manuals, technical specifications on websites, own examinations and calculations. In Table 3 the sources for each technology and peripherals are presented, and the extensive material inventory can be found in the supplementary excel files: 'Insulation_Heatemissionsystems_Ventilation', 'Total_materials_scenarios' and 'Technologies'. More extensive explanations on the calculations inside the model builder of ArcGIS can be found in Appendix 2 in the form of a step by step guide. In Appendix 3 a similar guide has been made for the environmental calculations inside the scientific software CMLCA. In the remainder of this chapter the calculations used for the formation of the material inventory in combination with the spatial data are explained and the main assumptions are presented.

	Source
Material requirements	
Natural gas system	Paper (Oliver-Solà, Gabarrell, & Rieradevall, 2009a)
Heat pumps	Paper (Greening & Azapagic, 2012)
Low and High temperature district heating	Paper (Oliver-Solà, Gabarrell, & Rieradevall, 2009b)
Insulation	Website/database (Nibe, n.d.)
Glass	Governmental documentations & own judgements (Krijnen, 2015a; 2015b; 2015c; 2015d; 2015e; 2015f)
Air vents	Website & own judgements (DucoTop 50 'ZR', n.d.)
Mechanical ventilation	Paper & Installation and user manual (Nyman & Simonson, 2005) (Vasco, 2013)
Radiator fan	Climatebooster manual & own judgements (ClimateBooster, 2017)
Induction hob	Paper (Pina, Elduque, Javierre, Martinez, & Jiménez, 2015)
Natural gas hob	Website & own judgements (Gamma, 2018) n
Material impact	
Environmental impact of all materials (excluding insulation)	Ecoinvent 3.4

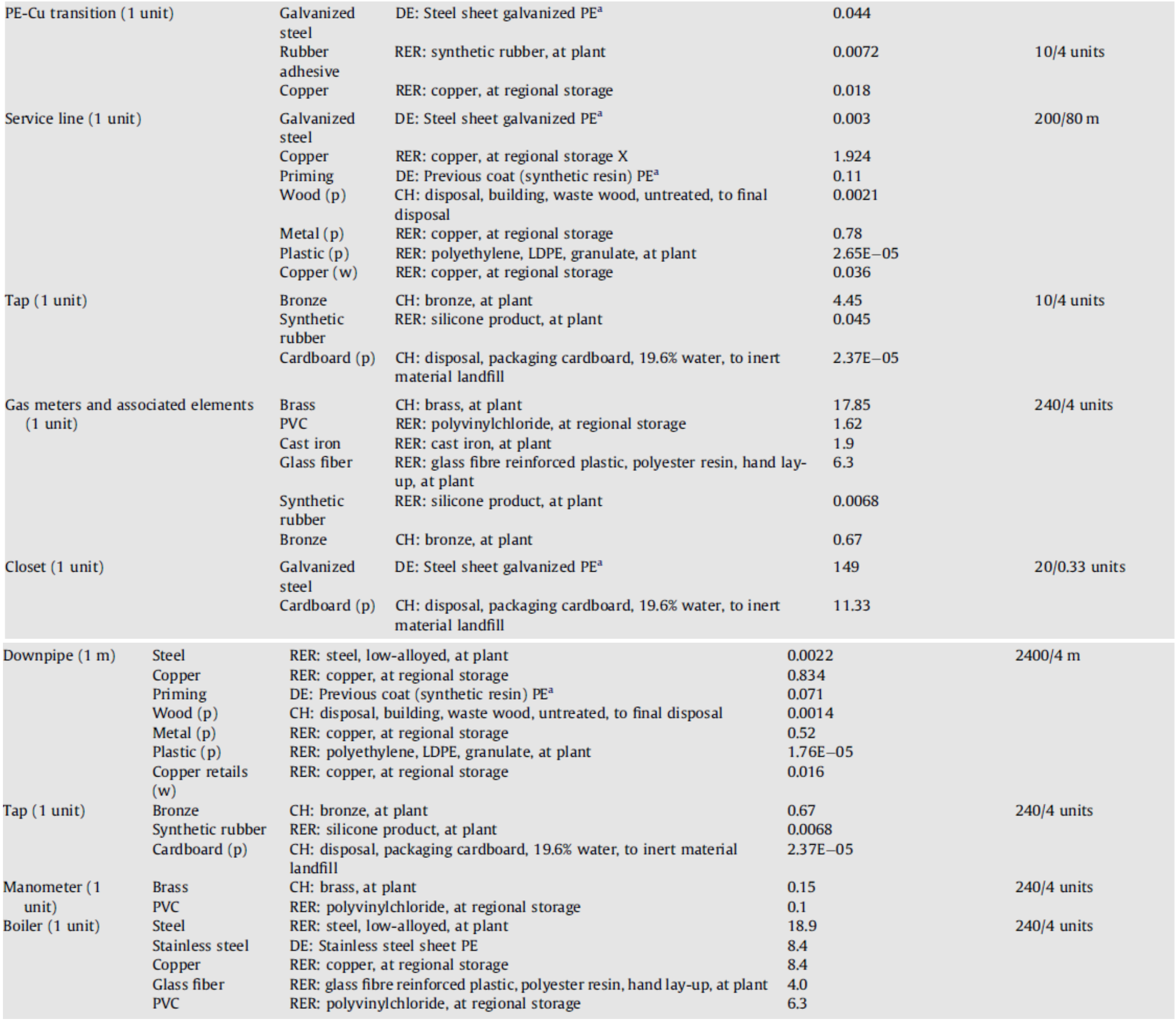
Table 3 The material data sources that are used in this thesis

4.1 Natural gas heat system

The materials that are contained in the gas network are calculated per dwelling by using the material inventory data created by Oliver-Solà et al. (2009a). His inventory is presented in Table 4. This inventory is based on a high- and low-density scenario. The low-density scenario has 4 buildings with 1 dwelling per building and in the high-density scenario there are 10 buildings per 100m of pipeline with 24 dwellings per building.



Component	Material	Process	Quantity in the component	Quantity in the scenario
Pipe (1 m)	HDPE	RER: polyethylene, HDPE, granulate	4.09 kg	100 m
Surface box (1 unit)	Water	RER: tap water, at user	228.48 kg	1 unit
	Sand	CH: sand, at mine	2078.84 kg	
	Limestone	CH: gypsum plaster board, at plant	135.51 kg	
	Cement	CH: cement, unspecified, at plant	431.91 kg	
	Cast iron	RER: cast iron, at plant	165.40 kg	
	Ceramic brick	RER: brick, at plant	1789.74 kg	
	Electricity	ES: electricity, low voltage, production ES, at grid	7.76 MJ	
Trench works (1 m)	Pavement	CH: cement, unspecified, at plant	21.40 kg	100 m
	Concrete	DE: concrete block, at plant	32.09 kg	
	Aggregates	CH: sand, at mine	403.09 kg	
	Diesel	GLO: diesel, bumed in building machine	34.53 MJ	



PE-Cu transition (1 unit)	Galvanized steel	DE: Steel sheet galvanized PE[a]	0.044	
	Rubber adhesive	RER: synthetic rubber, at plant	0.0072	10/4 units
	Copper	RER: copper, at regional storage	0.018	
Service line (1 unit)	Galvanized steel	DE: Steel sheet galvanized PE[a]	0.003	200/80 m
	Copper	RER: copper, at regional storage X	1.924	
	Priming	DE: Previous coat (synthetic resin) PE[a]	0.11	
	Wood (p)	CH: disposal, building, waste wood, untreated, to final disposal	0.0021	
	Metal (p)	RER: copper, at regional storage	0.78	
	Plastic (p)	RER: polyethylene, LDPE, granulate, at plant	2.65E−05	
	Copper (w)	RER: copper, at regional storage	0.036	
Tap (1 unit)	Bronze	CH: bronze, at plant	4.45	10/4 units
	Synthetic rubber	RER: silicone product, at plant	0.045	
	Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	2.37E−05	
Gas meters and associated elements (1 unit)	Brass	CH: brass, at plant	17.85	240/4 units
	PVC	RER: polyvinylchloride, at regional storage	1.62	
	Cast iron	RER: cast iron, at plant	1.9	
	Glass fiber	RER: glass fibre reinforced plastic, polyester resin, hand lay-up, at plant	6.3	
	Synthetic rubber	RER: silicone product, at plant	0.0068	
	Bronze	CH: bronze, at plant	0.67	
Closet (1 unit)	Galvanized steel	DE: Steel sheet galvanized PE[a]	149	20/0.33 units
	Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	11.33	
Downpipe (1 m)	Steel	RER: steel, low-alloyed, at plant	0.0022	2400/4 m
	Copper	RER: copper, at regional storage	0.834	
	Priming	DE: Previous coat (synthetic resin) PE[a]	0.071	
	Wood (p)	CH: disposal, building, waste wood, untreated, to final disposal	0.0014	
	Metal (p)	RER: copper, at regional storage	0.52	
	Plastic (p)	RER: polyethylene, LDPE, granulate, at plant	1.76E−05	
	Copper retails (w)	RER: copper, at regional storage	0.016	
Tap (1 unit)	Bronze	CH: bronze, at plant	0.67	240/4 units
	Synthetic rubber	RER: silicone product, at plant	0.0068	
	Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	2.37E−05	
Manometer (1 unit)	Brass	CH: brass, at plant	0.15	240/4 units
	PVC	RER: polyvinylchloride, at regional storage	0.1	
Boiler (1 unit)	Steel	RER: steel, low-alloyed, at plant	18.9	240/4 units
	Stainless steel	DE: Stainless steel sheet PE	8.4	
	Copper	RER: copper, at regional storage	8.4	
	Glass fiber	RER: glass fibre reinforced plastic, polyester resin, hand lay-up, at plant	4.0	
	PVC	RER: polyvinylchloride, at regional storage	6.3	

Table 4 Natural gas network inventory table by Oliver-Solà et al. (2009a)

In order to adjust the inventory made by Oliver-Solà to the Merenwijk, the building and dwelling density per 100 meters of pipelines was calculated for the Merenwijk (Table 6). This table is calculated by using the *gasleidingen* shapefile to calculate the total length of the gas network inside the Merenwijk. To find the amount of dwellings within the Merenwijk, the address and BAG 3D data layers are joined together. With the combination of Table 4 and Table 6 the inventory could be adjusted to meet the Merenwijk characteristics (Table 5). In the current model the building and dwelling density is added manually and is therefore not generic and dynamic.

Material	Kg/dwelling
Brass	18
Bronze	5.27
Cardboard	0.93
Cast Iron	17.62
Cement	244.41
Ceramic brick	170.08
Concrete	304.95
Copper	58.22
Galvanized steel	12.38
Glass fiber	10.3

HDPE	38.87
Limestone	12.88
Plastic	0.00049
Priming	2.02
PVC	8.02
Sand	4028.20
Stainless steel	8.4
Steel	18.90
Synthetic rubber	0.06
Wood	0.04

Table 5 Material inventory for the implementation of the gas network

Number of dwellings per 100 m pipeline	11
Amount of buildings per 100m pipeline	9
Meters of pipeline	39685
Number of dwellings in the Merenwijk	4176
Number of buildings in the Merenwijk	3691

Table 6 General characteristics of the Merenwijk

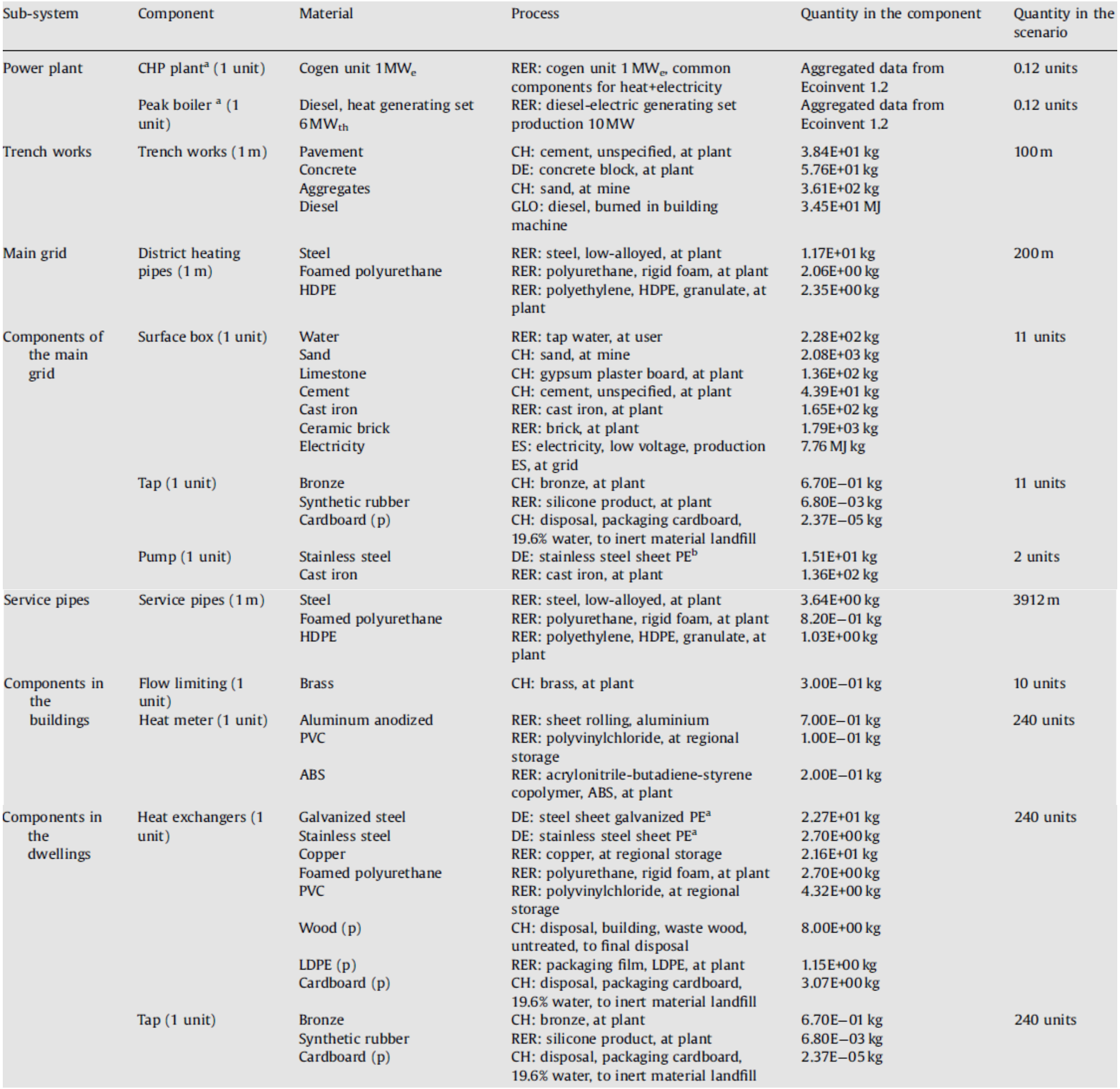
Not only the natural gas heat system will be abandoned, but also the natural gas hobs will be replaced by induction hobs. In order to calculate the materials contained in the natural gas hobs, the total weight of the ETNA A124VRVSA is used, in combination with the known materials used in this gas hob (Gamma, 2018) and own judgements by weighting and inspecting a regular natural gas hob (Appendix 4). All of this together resulted in Table 7. The corresponding materials from Table 5 & Table 7 were added up and multiplied by the total amount of dwellings in the Merenwijk in order to estimate the used material inside the gas network that will become available after natural gas is abandoned as a heat source.

Materials	Kg/unit
Stainless steel	8.4
ABS-PC	0.1
Cast iron	4

Table 7 Material inventory for a natural gas hob

4.2 District heating

District heating needs a widespread infrastructure on a relatively large scale. It also needs some minor adjustments inside the buildings to make it work. The data that was used to calculate the materials used for the implementation of this district heat network comes from another paper by Oliver-Solà et al. (2009b). His inventory is presented in Table 8. For this inventory Oliver-Solà used a density of 10 buildings with 24 dwellings per building per 100 meter of network pipelines.



Sub-system	Component	Material	Process	Quantity in the component	Quantity in the scenario
Power plant	CHP plant[a] (1 unit)	Cogen unit 1 MW_e	RER: cogen unit 1 MW_e, common components for heat+electricity	Aggregated data from Ecoinvent 1.2	0.12 units
	Peak boiler [a] (1 unit)	Diesel, heat generating set 6 MW_{th}	RER: diesel-electric generating set production 10 MW	Aggregated data from Ecoinvent 1.2	0.12 units
Trench works	Trench works (1 m)	Pavement	CH: cement, unspecified, at plant	3.84E+01 kg	100 m
		Concrete	DE: concrete block, at plant	5.76E+01 kg	
		Aggregates	CH: sand, at mine	3.61E+02 kg	
		Diesel	GLO: diesel, burned in building machine	3.45E+01 MJ	
Main grid	District heating pipes (1 m)	Steel	RER: steel, low-alloyed, at plant	1.17E+01 kg	200 m
		Foamed polyurethane	RER: polyurethane, rigid foam, at plant	2.06E+00 kg	
		HDPE	RER: polyethylene, HDPE, granulate, at plant	2.35E+00 kg	
Components of the main grid	Surface box (1 unit)	Water	RER: tap water, at user	2.28E+02 kg	11 units
		Sand	CH: sand, at mine	2.08E+03 kg	
		Limestone	CH: gypsum plaster board, at plant	1.36E+02 kg	
		Cement	CH: cement, unspecified, at plant	4.39E+01 kg	
		Cast iron	RER: cast iron, at plant	1.65E+02 kg	
		Ceramic brick	RER: brick, at plant	1.79E+03 kg	
		Electricity	ES: electricity, low voltage, production ES, at grid	7.76 MJ kg	
	Tap (1 unit)	Bronze	CH: bronze, at plant	6.70E−01 kg	11 units
		Synthetic rubber	RER: silicone product, at plant	6.80E−03 kg	
		Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	2.37E−05 kg	
	Pump (1 unit)	Stainless steel	DE: stainless steel sheet PE[b]	1.51E+01 kg	2 units
		Cast iron	RER: cast iron, at plant	1.36E+02 kg	
Service pipes	Service pipes (1 m)	Steel	RER: steel, low-alloyed, at plant	3.64E+00 kg	3912 m
		Foamed polyurethane	RER: polyurethane, rigid foam, at plant	8.20E−01 kg	
		HDPE	RER: polyethylene, HDPE, granulate, at plant	1.03E+00 kg	
Components in the buildings	Flow limiting (1 unit)	Brass	CH: brass, at plant	3.00E−01 kg	10 units
	Heat meter (1 unit)	Aluminum anodized	RER: sheet rolling, aluminium	7.00E−01 kg	240 units
		PVC	RER: polyvinylchloride, at regional storage	1.00E−01 kg	
		ABS	RER: acrylonitrile-butadiene-styrene copolymer, ABS, at plant	2.00E−01 kg	
Components in the dwellings	Heat exchangers (1 unit)	Galvanized steel	DE: steel sheet galvanized PE[a]	2.27E+01 kg	240 units
		Stainless steel	DE: stainless steel sheet PE[a]	2.70E+00 kg	
		Copper	RER: copper, at regional storage	2.16E+01 kg	
		Foamed polyurethane	RER: polyurethane, rigid foam, at plant	2.70E+00 kg	
		PVC	RER: polyvinylchloride, at regional storage	4.32E+00 kg	
		Wood (p)	CH: disposal, building, waste wood, untreated, to final disposal	8.00E+00 kg	
		LDPE (p)	RER: packaging film, LDPE, at plant	1.15E+00 kg	
		Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	3.07E+00 kg	
	Tap (1 unit)	Bronze	CH: bronze, at plant	6.70E−01 kg	240 units
		Synthetic rubber	RER: silicone product, at plant	6.80E−03 kg	
		Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	2.37E−05 kg	

Table 8 District heat network material inventory by Oliver-Solà et al. (2009b)

The data out of this paper is adjusted in the same way as the paper for the natural gas system. Therefore, the building and dwelling density that was already calculated for the natural gas system was also used to translate the data from Oliver-Solà et al. (2009b) to the Merenwijk. This resulted in the inventory of Table 9. Implementing the high temperature district heat network nothing has to change besides the heat technology and the cooking technology. Therefore, the same method could be used as was used to calculate the materials contained in the natural gas heat network and the natural gas hob. The materials needed for the district heat network (Table 9) and the induction hob (Table 18) were added and multiplied by the amount dwellings inside the Merenwijk.

However, for the low temperature district heating more adjustments need to be made in order to meet the low temperature implementation requirements. The material inventory for both the heat network and induction hob was put in the ArcGIS model builder together with the inventories for insulation, glass, air vents, mechanical ventilation and radiator ventilators (Appendix 2: Figure 36). These inventories are dependent on spatial characteristics of the buildings in the Merenwijk and will be further discussed after subsection 4.3 Heat pumps.

Material	Kg/dwelling
ABS	0.2
Aggregates (sand)	3430.65
Aluminium anodized	0.7
Brass	0.265
Bronze	1.50
Cardboard	3.07
Cast iron	187.37
Cement	42.97
Ceramic brick	1752.21
Concrete	547.38
Copper	21.6
Foamed polyurethane	55.22
Galvanized steel	22.7
HDPE	62.60
Limestone	133.13
Pavement	364.92
PVC	4.42
Sand	2036.10
Stainless steel	5.57
Steel	281.71
Synthetic rubber	0.02
Water	223.19
Wood	8

Table 9 Material inventory for the implementation of district heat network

4.3 Heat pumps

The other low temperature more sustainable heat alternative in this thesis is the heat pump. In this thesis an air-water heat pump is used as one of the alternatives for natural gas. The data on the materials that are contained in an air-water heat pump are retrieved from the paper by Greening & Azapagic (2012). In this paper they created an inventory of an air-water heat pump with a capacity of 10 kW. To make it fit the scope of this thesis some material or material related data, such as fuels and materials that are used during the lifespan of the heat pump or related technologies, were left out. Table 10 presents the material inventory of the heat pump that is used in the model and is put into the model builder of ArcGIS, together with the material inventory of the induction hob. The heat pumps also deliver low temperature heat and therefore the same building adjustments should be made as for the low temperature district heat network.

Materials	Kg/unit
Copper	36.7
Elastomere	16
HDPE	0.5
Polyolester oil	2.7
Polyvinylchloride	1.6
R-134a	4.9

Reinforcing steel	120
Steel	32

Table 10 Material inventory for the implementation of a heat pump

4.4 Insulation

One of the building adjustments that is needed for the implementation of low temperature technologies is the upgrade in insulation. To calculate the needed insulation materials the database of Nibe, governmental and construction related websites, expert judgements and the flyers from *woonwijzerwinkel* (Appendix 1) were used.

Table 11 presents the insulation values that are needed for the implementation of low temperature heat pumps. In this thesis another low temperature alternative is taken into account, the low temperature district heating. The minimal insulation values used for the heat pumps are also used for the implementation of the low temperature district heat network.

Minimum insulation values for implementing a low temperature heat pump	
Floor	$Rc \geq 3.5$
Roof	$Rc \geq 3.5$
Wall	$Rc \geq 0.9$
Glass	$U \leq 1.2$

Table 11 Low temperature heat pump requirements for any residential building (flyer: Naar nul met: Warmtepomp (woonwijzerwinkel Appendix 1) & expert judgement (Sabine Jansen))

To find out what the current insulation situation is in the residential buildings, they were split into 8 groups based on their construction year:

- Before 1930
- 1930 - 1945
- 1946 – 1964
- 1965 – 1974
- 1975 – 1982
- 1983 – 1987
- 1988 – 1991
- 1992 – 2005

These groups were based on the flyers from the *woonwijzerwinkel* (Appendix 1) and the website *bestaandewoningbouw* (Liebregts & Persoon, 2011). In order to calculate the total material that would be needed for every construction year period the following formula was used:

$$Rm = \frac{\mathrm{d}}{\lambda}$$

Rm = Heat resistance of the material in m^2 K/W

d = thickness of the material in meters

λ = conductivity of the material in W/m K

The added insulation value (Rm) for these adjustments was calculated by taking the difference between the minimal required Rc values (Table 11) and the Rc values that currently present in the residential buildings (Table 1). The λ (0.035 W/m K) was taken from the Nibe database for glass wool. The only unknown is now the thickness of the glass wool that is needed for every construction year period (d). Multiplying Rm with λ will result in the thickness of glass wool per m^2. With the required thickness of insulation known, only the kilogram of glass wool per m$^{2\text{ is}}$ needed to implement this data in the model and combine it with the total area that are present in the BAG 3D layer. The amount of glass wool in kilogram per m^2 was also retrieved from the Nibe database. However, there is an exception for this method and that is for the cavity walls. Empty cavity walls cannot be partially insulated when using glass wool flakes. That means that the recommended Rc values, needed to implement heat pumps, will be exceeded and the thickness of the empty wall was used as the minimal material thickness. For that reason, also the Rc values after renovation were calculated and presented in Table 12. The entire insulation calculation table can be found in the supplementary excel file: 'Insulation_Heatemissionsystems_Ventilation'.

1930 - 1945 (Energy label: G)	**Location**	Material	W/mK	Rc value present (m2K/W)	Rc value needed	Cavity wall thickness (mm)	Material thickness needed (mm)	Materials in kilogram per m2	Rc value after renovation
	Underfloor	Glass wool plates	0.035	0.15	3.5		117.25	3.85	3.5
	Inside roof	Glass wool plates	0.035	0.22	3.5		114.8	3.77	3.5
	Cavity wall	Glass wool flakes	0.035	0.4	0.9	30	30	0.99	1.3

Table 12 Material inventory calculations on the amount of glass wool that is needed for floor, wall and roof insulation in the buildings' construction year period 1930-1945

4.4.1 Floor

To implement the insulation needed per m^2 in the BAG 3D layer, the floor area is already present in the dataset and is equal to the Shape_Area.

4.4.2 Wall

The total wall area is calculated by multiplying the Av_Shape_Length by the total height of the building. This is only for the flat roofed buildings. The pitched roofs buildings are assumed to be the buildings with 2 or less addresses per building. For this type of buildings, the wall area is calculated by multiplying the Av_Shape_Length by the total height of the building minus the roof areas height (3 meters) multiplied by the Av_shape_length times 0.75. The 0.75 is the result of calculating the non-wall areas on the upper floor. The two side views do not have any wall area, while the front and back view have a triangular wall area. There is assumed that the front and back wall area together are equal to a square and there is assumed that the building is a square, that means the length of the sides is equal to the length of the front and back side of the building. Now for both types of roofs on the buildings the Wall_Window_Area is calculated included with the windows. To exclude the windows and have the entire wall area that needs to be insulated the entire wall area is multiplied by the wall/window ratio (100% minus the percentage windows from Table 13) and that results in the Wall_Area. A visual presentation of the wall calculations is given in Figure 13.

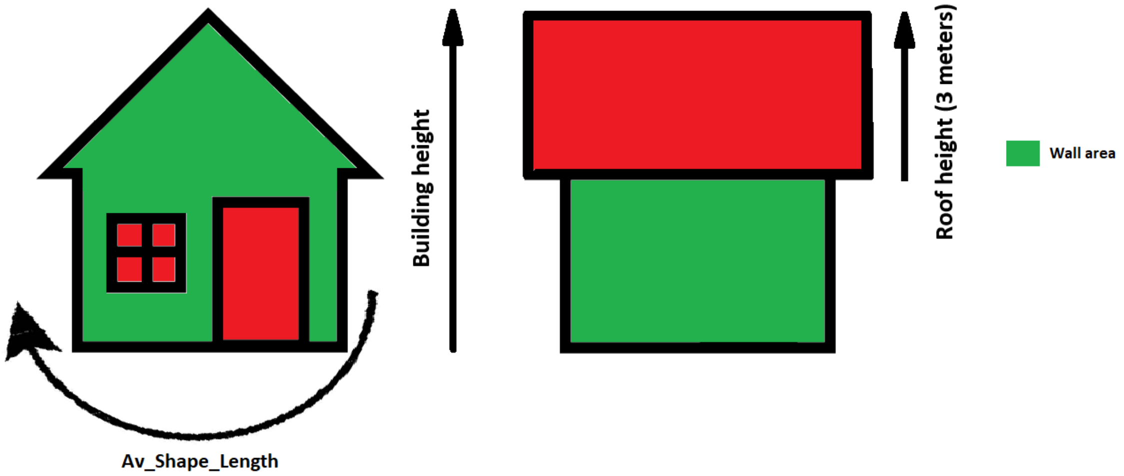


Figure 13 Front and side view of a pitched roof building. The green areas present the wall areas that are included in the wall area insulation calculation

4.4.3 Roof

As we saw with the calculations for the wall area, the buildings with more than 2 addresses inside the roof is assumed to be flat. For these buildings the Roof_Area is equal to the Shape_Area multiplied by the roof/window ratio (100% minus the percentage windows from Table 13), to eliminate the areas that are windows. When there are 2 or less addresses per building (Pitched roof) the Roof_Area is calculated by assuming that the Roof_Area is 1.5 times the size of the Shape_Area. To extract the windows from this area the results were multiplied by the roof/window ratio. The total roof area is presented in the BAG_3D data set as Roof_Area (Appendix 2: Figure 33 (5)).

In the end all glass wool insulated areas (Floor/wall/roof) are added together and multiplied by the kilograms of glass wool per m^2 inside the model builder of ArcGIS for each individual building.

4.5 Glass

All buildings that are older than 2005 will replace their windows by HR ++ glass, since the standard for these buildings is to have maximum double glassed windows. In order to calculate the amount of glass and argon gas that is needed to implement the HR++ glass the amount of windows per building are needed. To calculate the amount of windows in a building, I calculated the wall/window ratio for each type of building, because no other data on the area of glass is available. To add this data, I estimated the average percentage of windows of the total wall area for 6 different building types, as can been seen in Table 13 by using *referentiewoningen* documents provided by the RVO (Krijnen, 2015a; 2015b; 2015c; 2015d; 2015e; 2015f). With these percentages I calculated the total window area by using the same formula as is used for the calculation of the wall and roof area, but instead of the wall/window and the roof/window, the window/wall and window/roof ratio will be used of Table 13 and multiplied by the Wall_Window_Area and Roof_Window_Area and then added together. The result of this calculation is the total glass area calculated per type of building (Glass_Area). In the ArcGIS model the Glass_Area is multiplied with the material requirements of HR++ glass per m^2 (Table 14) in order to calculate the total glass requirements in the low temperature heating scenario.

Type of building	**% windows of total wall area**	**% windows of total roof area**
Semidetached house	15%	2%
Detached house	19%	3%
Intermediate house	40%	2%
Corner house	19%	2%

Gallery complex	35%	0%
Apartment block	49%	0%

Table 13 Percentage of windows per wall and roof area

Materials	**kg/m²**	**m³/m²**
Argon gas		0.015
Glass	23	

Table 14 Materials used in HR++ glass

4.6 Air vents

To calculate the materials that are needed for the implementation of air vents, the total length of the DucoTop 50 ‘ZR’ is needed and is calculated by the following formula:

$$m = \frac{V_c * a}{A_c}$$

m = Meters of DucoTop 50 ‘ZR’

V_c = Ventilation capacity

a = Total surface area

A_c = Air vent capacity (14.8 $dm^3/s/m$ for DucoTop 50 ‘ZR’)

The total residential surface area is one of the unknowns and could be calculated using the following formula:

$$a = \frac{h}{3} * f * r$$

a = Total residential surface area

h = Height of building

f = Surface area floor

r = Percentage of residential surface area

The 3 under the h stands for 3 meters and is the average height of one floor. Dividing the height of the building by the average height of one floor will result in the number of floors inside the residential building. On each floor there are also different rooms: lounges, toilet rooms, bathrooms, technical rooms and storage rooms. In *het bouwbesluit 2012* there are requirements set for the minimal ventilation that is needed in the residential buildings. The different rooms are split into two groups, residential areas and the other areas. The residential areas in residential buildings must be at least 55% (r) of the total area and their ventilation capacity (V_c) must be at least 6 $dm^3/s/m^2$ (Bouwbesluit 2012). In the remaining areas the supply of fresh air is provided by chinks under the doors to let the air flow from one room to another and no additional ventilation is needed. Multiplying the number of floors in the building by the floor surface area and the percentage of residential surface area resulted in total residential surface area (a). With ‘a’ calculated the total meters of air vents that are needed inside the building were calculated by multiplying ‘a’ with V_c and dividing that by the capacity of the DucoTop 50 ‘ZR’ (A_c). With the meters of DucoTop 50 ‘ZR’ that are needed for each building known, it could be multiplied by the amount of materials inside the DucoTop 50 ‘ZR’ per meter (Table 15) to calculate the materials needed per individual dwelling. For the three materials used in the DucoTop 50 ‘ZR’ the formula was added inside the model builder of ArcGIS.

Materials	kg/m
Aluminium	1.05
Polyurethane	0.0138125
Synthetic rubber	0.2

Table 15 Materials used in one meter of DucoTop 50 ‘ZR’

4.7 Mechanical ventilation

Only the residential buildings that have a construction year that is older than 1983, the ventilations system has to be replaced by a mechanical ventilation system. This is calculated by selecting all buildings that are built before 1983 and multiplying that by the material requirements for a mechanical ventilation system (Table 16).

Materials	kg/unit
ABS	0.13
Aluminium	0.6
Cardboard	0.95
Copper	0.615
Natural rubber	0.303
Paper	0.1
Polyethylene	0.78
Polyurethane	0.07
PVC	1.155
Steel	2.4

Table 16 Materials used in a mechanical ventilator

4.8 Heat emission systems

The amount of radiator fans that are needed depends on the amount of radiators and the size of the radiators that are in the residential buildings. To calculate the amount of radiator fans that are needed, the total volume of a building (V_b) was calculated using the height (h) and floor area (f). For the buildings with a pitched roof the total volume was calculated by extracting 3 meters from the total height and multiplying that by the total floor area. This resulted in the total volume without a pitched roof (V_s). Now to calculate the volume of the pitched roof, the total floor area was multiplied by 3 meters and that was again multiplied by 0.5 to calculate the volume in a pitched roof (V_p). The 3 means 3 meters and that is assumed as the floor height and the 0.5 is used because there is assumed that the pitched roofs are all triangular shaped.

$$V_s = (h - 3) * f$$

$$V_p = 3 * f * 0.5$$

$$V_{\boldsymbol{b}} = V_p + V_s$$

V_s = Total volume of all floors minus the upper floor of the pitched building

h = Height of building

f = Surface area floor

V_p = Total volume of the pitched roof

V_b = Total volume of the building with a pitched roof

With the total volume of the buildings known the total capacity of radiation was calculated by multiplying the total volume by 85 Watt. The 85 Watt is the average recommended temperature that is needed per room. Assuming that the average radiator capacity is 1500 Watt resulted in dividing the total capacity by the average capacity of a radiator to calculate the amount of radiators that are present inside the buildings and the amount of radiator fans that are needed. The materials of a radiator fan were calculated per unit (Table 17) and were multiplied by the result of how many units are needed per individual building.

Materials	Kg/unit
ABS	0.874
ABS-PC	0.04176
Aluminium	1.43
Cardboard	0.2
Copper	0.148
Neodymium Iron Boron Magnet	0.16
PVC	0.133
SEBS (synthetic rubber)	0.3

Table 17 Materials used in a radiator ventilator

4.9 Induction hob

I assume that all dwellings still use natural gas hobs to cook on and all dwellings will need to replace their natural gas hob by an induction hob. All dwellings were multiplied by the materials that are needed for one induction hob as is presented in Table 18.

Materials	kg/unit
Aluminium	1.519
Cardboard	0.285
Copper	1.125
EPS	0.466
Ferrite	0.496
LDPE	0.086
PA66	1.999
Paper	0.345
PPS	0.76
PVC	0.161
Steel	0.457
Vitroceramic glass	2.903

Table 18 Materials used in an induction hob

In the supplementary excel files: ‘Technologies’ and ‘Insulation_Heatemissionsystems_Ventilation’ more details on the material inventory calculations for the technologies and insulation, heat emission systems and ventilation requirements for low temperature heat technologies can be found.

4.10 Environmental impact calculations

In second part of the thesis material inventories were used to model the environmental impact of the materials that are required for the heat transition. To model the environmental impact of these materials an LCA program called CMLCA 6.1, that is linked to ecoinvent 3.4, was used. In this program the environmental impact was calculated per material per scenario by multiplying the impact of one kilogram of material or one unit by the amount of kilograms of material that are needed for the heat transition. The impact is calculated from cradle to the market. The impact categories were divided into the 9 CML2001_Baseline, reference World, 2000 categories:

- Acidification potential (SO2-eq)
- Climate change (CO2-eq)
- Eutrophication potential (PO4-eq)
- Freshwater aquatic ecotoxicity (1,4-DCB-eq)
- Human toxicity (1,4-DCB-eq)
- Photochemical oxidation (ethylene-eq)
- Depletion of abiotic resources (antimony-eq)
- Stratospheric ozone depletion (CFC-11-eq)
- Terrestrial ecotoxicity (1,4-DCB-eq)

The calculations on these impact categories are done per kilogram of materials per material type and are implemented into the model builder of ArcGIS. A step by step guide of this can be found in Appendix 2 and 3.

4.11 Assumptions

Based on the scenarios presented in the scenario chapter, I estimated the material requirements and their environmental impact per scenario in the Merenwijk. To calculate that amount several simplifications were made to disaggregate data from LCA papers and the data inventory from the Nibe website. The simplifications that were made, are on the characteristics of the technologies, insulation, ventilation and buildings. The main assumptions that are made in this thesis are:

- Not every building has the same boiler installed in the Netherlands, some have an HR boiler, some others a boiler and a geyser, but in this research I assumed that every residential building that is not connected to the district heat network has a natural gas boiler. This assumption was also made for the other technologies, that when choosing for a renewable technology everyone will chose for the same technology. I assume that the different brands in technologies will not differ significantly in the materials that are used inside their technology.
- When there are more than 2 addresses in a building, then there is a flat roof that is the size of the building shape area. When there are 2 or less addresses per building, I assume there is a pitched roof that is 1.5 times the size of the building shape area. I could have handpicked the flat roofs doing a field study, but that would have taken a considerable amount of time and was not part of the generic model I wanted to create.
- The height of one floor is assumed to be 3 meters
- Rc value of cavity wall insulation to fit heat pumps into houses must be larger than 0.9, in contrast to the 1.8 that was mentioned in the flyers from the *woonwijzerwinkel* (Appendix 1). The Rc value of 0.9 and larger only counts when the rest of the building is insulated as the *woonwijzerwinkel* advices.
- To calculate the window/wall ratio, without available data for the building type, I assumed that all the buildings that had more than 2 addresses are gallery complexes and all buildings with 1 or 2 address are intermediate houses. For the calculations for all window/wall ratios I used the *referentiewoningen* 2015 (2015a; b; c; d; e; f). These are measurements and criteria for buildings that are not mandatory but can be used as an indicator for new build buildings. Older data was not available, so all periods are based on these *referentiewoningen*.
- For the floor insulation I assume that every building has a crawlspace underneath and insulation material can be put underneath the floor.
- To also take the upgrades in residential buildings into account, I assumed that all energy labels account for a certain construction year period and their related minimum insulation values (Table 19 & Table 1).

Energy label	Construction year
A	> 2005
B	> 2005
C	1983 - 1987
D	1975 - 1982
E	1965 - 1974
F	1946 - 1964
G	1930 - 1945

Table 19 Energy labels matched to a construction year period

- The average capacity of a radiator is 1500W and needs one radiator fan.
- I assumed that all pitched buildings upper floor is also 3 meters high and all pitched roofs have a triangular shape.

5. Results

The results chapter is split into three parts. In the first part the material requirements for the four different scenarios will be presented and compared to the current scenario of natural gas. In the second part of the results the environmental impact of the required materials will be presented and the climate change impact, ozone depletion and terrestrial ecotoxicity will be highlighted. In the last part the results are presented when the model is run for Leiden and these results are compared to the results of the Merenwijk.

5.1 Material requirements for the scenarios

The material requirements differ strongly per scenario, from 0 to 22.8 million kilograms. In Figure 14 a few things stand out: Natural gas and high temperature district heating do not require any insulation materials, natural gas scenario scores lowest on plastics and metals, natural gas scenario scores lower on trench backfilling materials than the district heat network, heat pumps score relatively low on all material groups except from insulation materials and low temperature district heating scores highest in all material groups. In the next subsections the groups of materials will be split into individual materials per scenario.

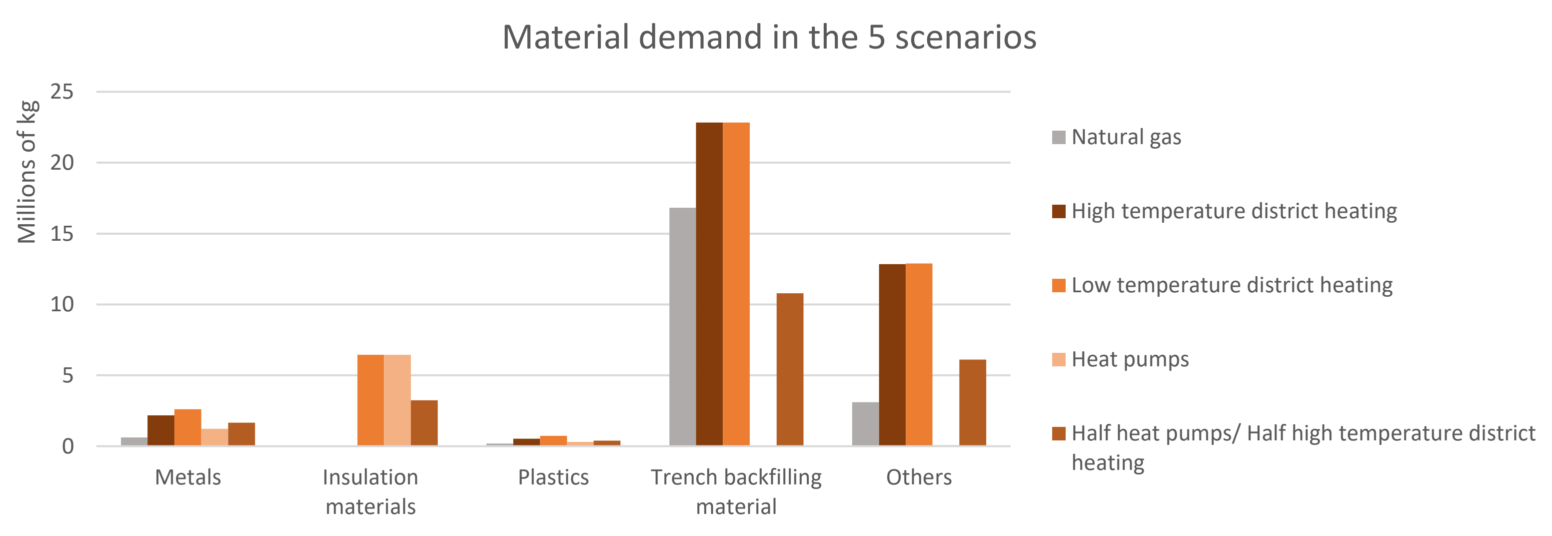


Figure 14 Material requirements for the current scenario and the possible four sustainable alternatives

5.1.1 All high temperature district heating

In the high temperature scenario, the main material requirements are the aggregates, sand and ceramic bricks (Figure 15). There is 14.3 million kilograms of aggregates needed, 8.5 million kilograms of sand and 7.3 million kilograms of ceramic bricks. The aggregates are needed to fill the trenches that could each be 3 meters deep. The ceramic bricks and sand are needed to build and implement the surface boxes of the main grid.

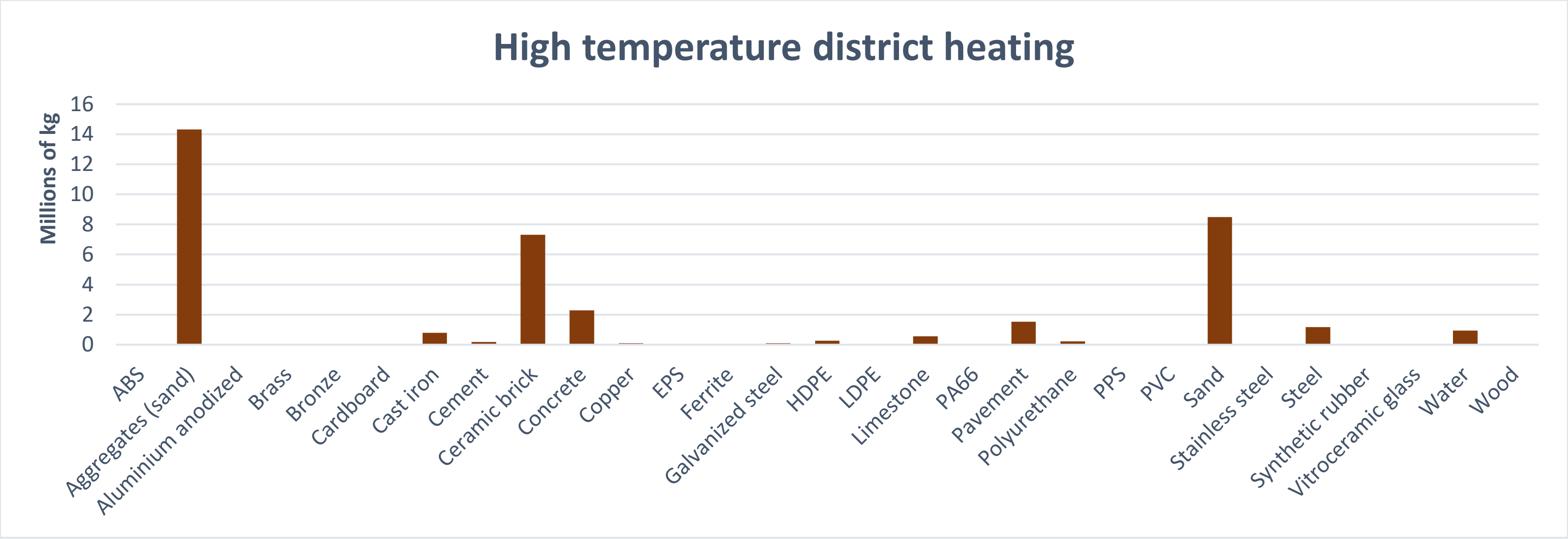


Figure 15 Kilogram of materials needed in high temperature district heating scenario

5.1.2 All low temperature district heating

The main difference between the low and high temperature scenario is the amount of different materials that are needed. In the low temperature scenario, the same materials are needed as in the high temperature scenario, but additionally there are also insulation, heat emission system and ventilation materials needed to meet the low temperature heating requirements (Figure 16). Therefore, this scenario does not only need a high amount aggregates ceramic bricks and sand, but also a significant amount of glass (4.7 million kilograms) and glass wool (1.7 million kilograms).

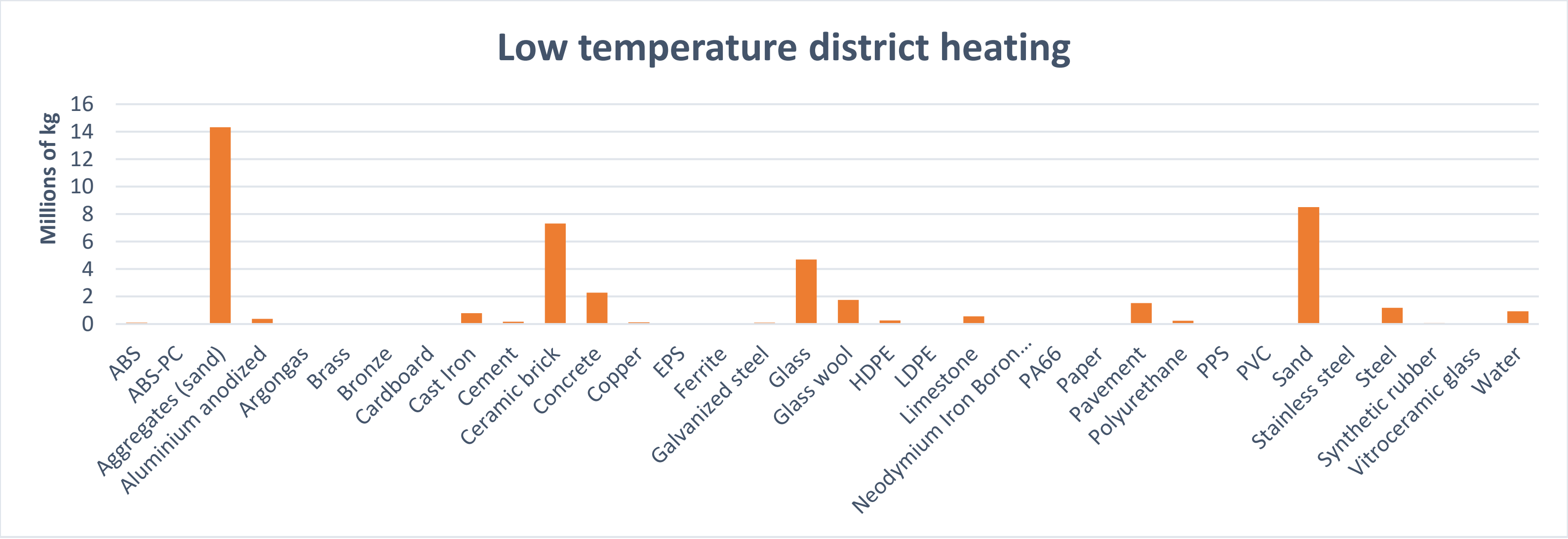


Figure 16 Kilogram of materials needed in low temperature district heating

5.1.3 All heat pumps

In this scenario less materials are needed compared to the previous 2 alternative scenarios. Because the heat pumps do not require any trench works and only require individual heat pumps within the buildings, the heat technology do not require a large amount of materials. However, the heat pumps are also low temperature heat sources and does require additional insulation, ventilation and heat emission systems. The materials that do stand out in this scenario are the demand for glass (4.7 million kilograms) and glass wool (1.7 million kilograms). Both materials count for approximately 80% of the total material requirement, as can be seen in Figure 17.

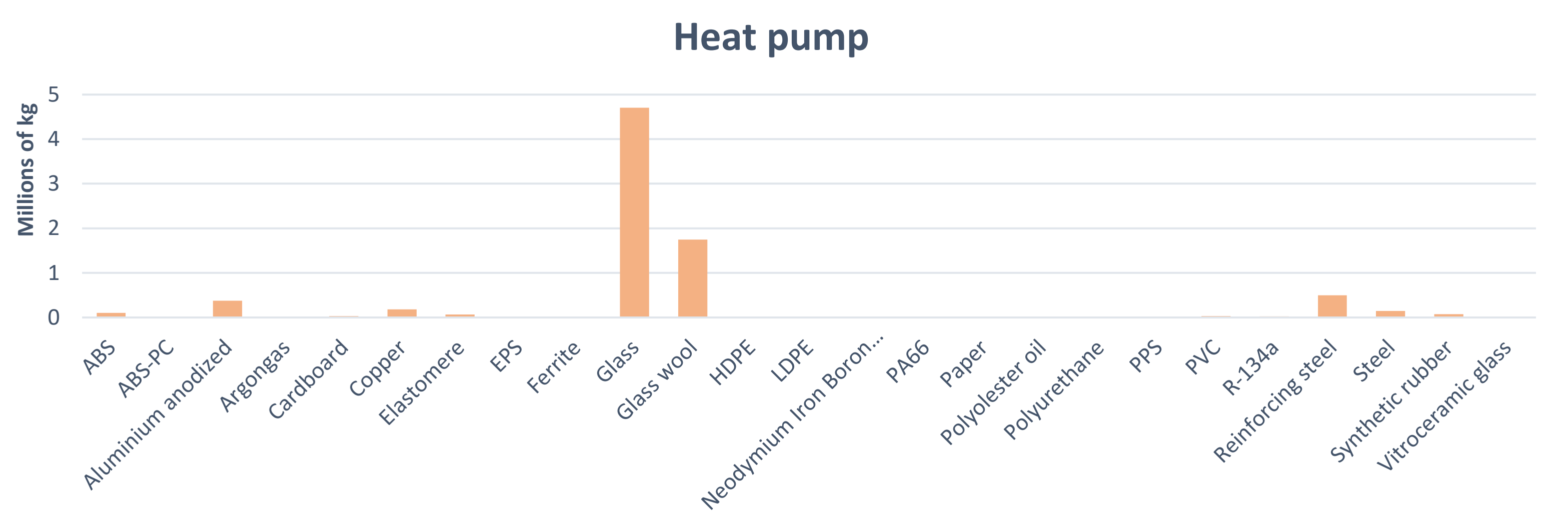


Figure 17 Kilograms of materials needed heat pump scenario

5.1.4 Half heat pumps/ Half high temperature district heating

This scenario combines both the heat pumps and high temperature district heating scenario together. In this scenario there are 6.8 million kilograms of aggregates needed, 4 million kilograms of sand, 3.5 million kilograms of ceramic bricks, 2.4 million kilograms of glass, 1 million kilograms of concrete and 0.9 million kilograms of glass wool (Figure 18).

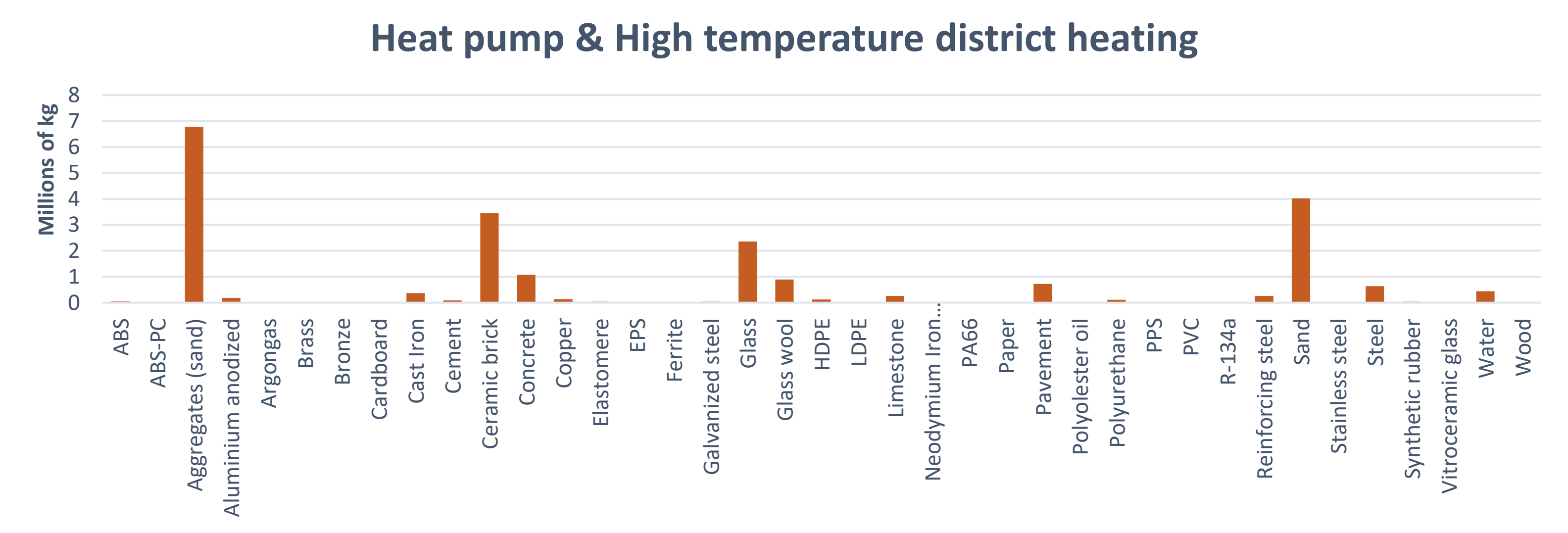
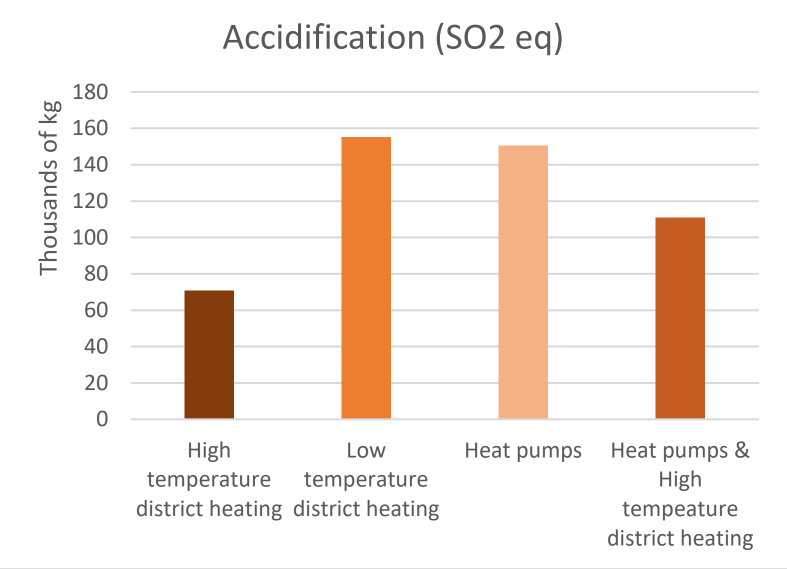


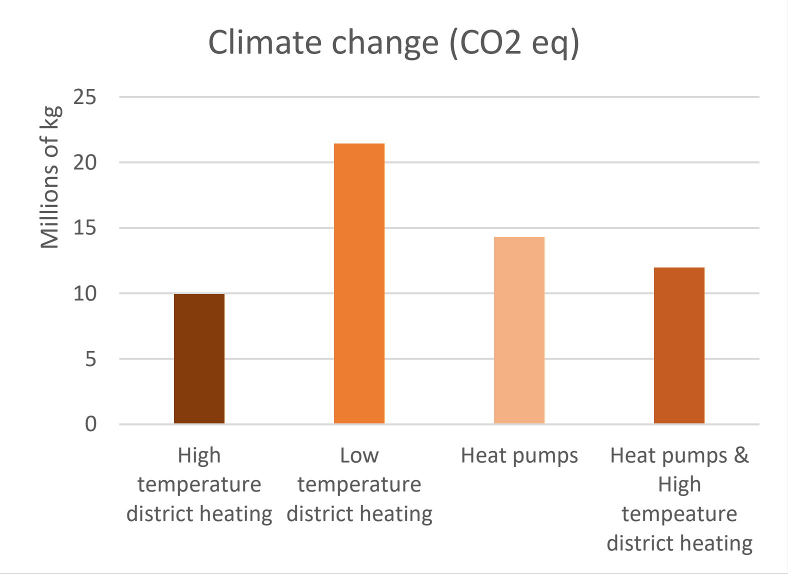
Figure 18 Kilogram of materials needed in heat pump & high temperature district heating scenario

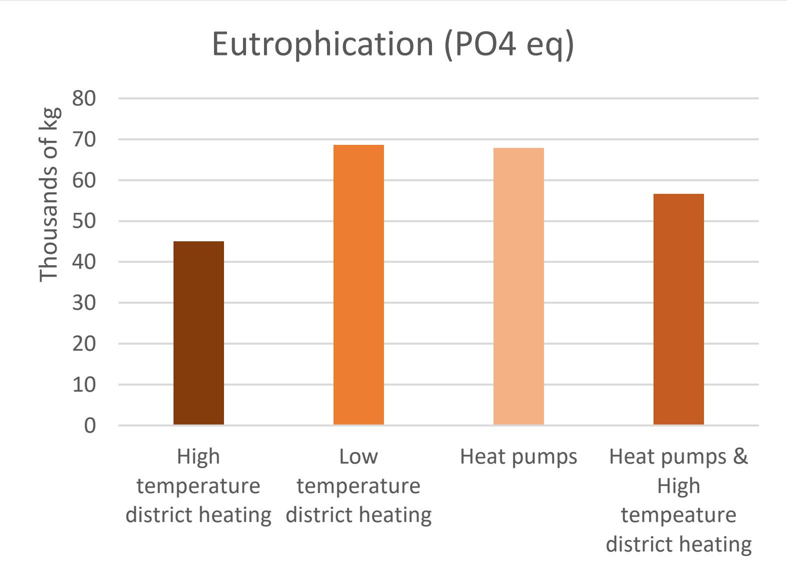
In all the scenarios the materials needed for insulation, trenches and the surface boxes are the main contributers to the amount of material that is needed. For the trenches and surface boxes this is directly related to the implementation of the technology, but for low temperature scenarios this is an indirect consequense of the implementation of low temperature technologies.

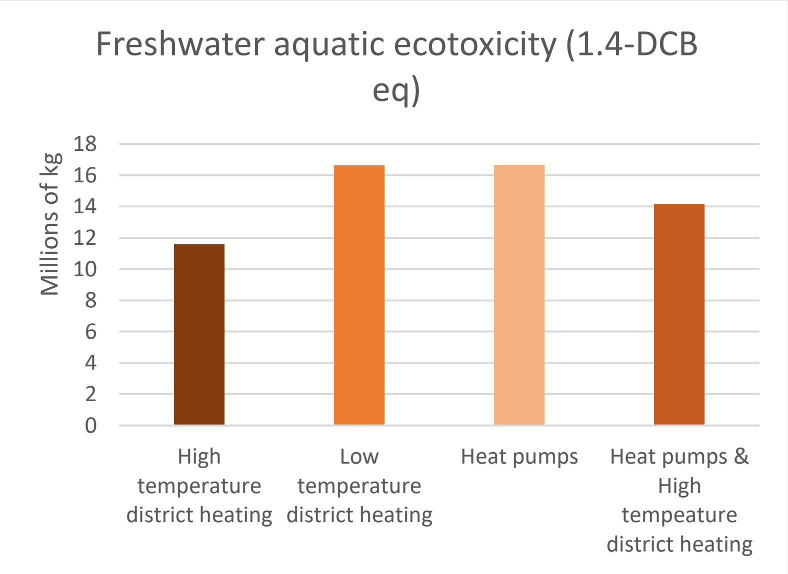
5.2 Material environmental impacts

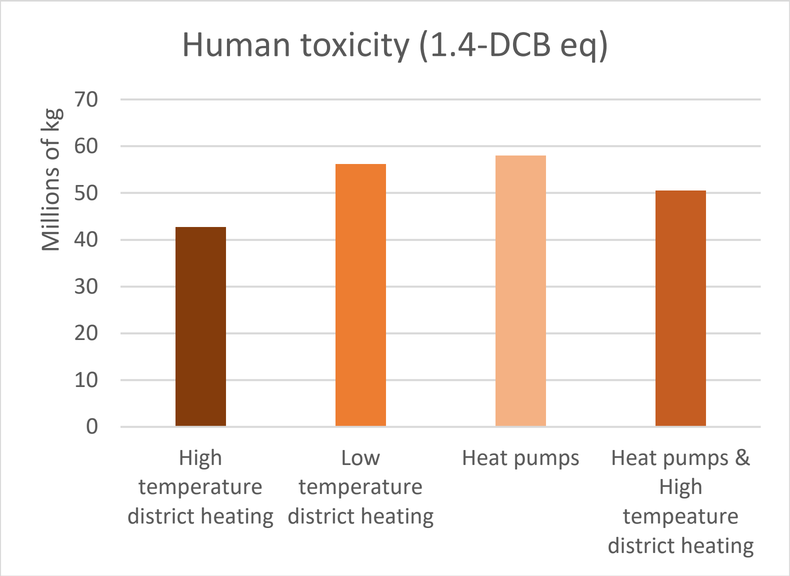
There are quite some differences between the scenarios in the impact categories. It stands out that in 8 out of 9 categories the high temperature district heating performs best in terms of environmental impact. This can be explained by the lack of insulation in this scenario, while the other scenarios all require some insulation. It also stands out that in 6 out of 9 categories the low temperature district heating scores the worst. This can be explained by insulation that is needed and the large amount of materials that is required in the network compared to the heat pump technology. Two other patterns that are visible within the environmental impact categories are the almost equal impacts in terms of kilograms between the low temperature district heating and the heat pump scenario (4 out of 9 categories) and on the other hand the significantly higher impact of the low temeprature district heating scenario compared to the heat pumps (3 out of 9 categories). The impact categories that break the trend and do not seem to follow any of these patterns are the stratospheric ozone depletion and terrestrial ecotoxicity.

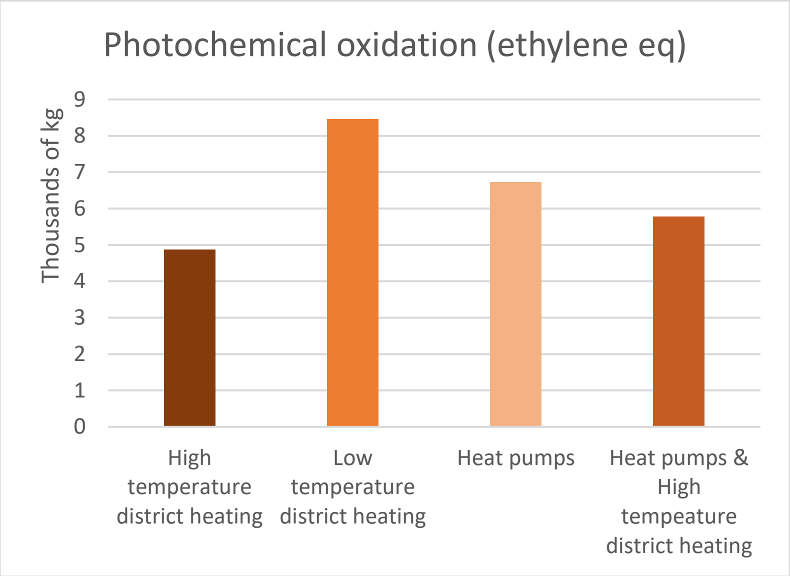


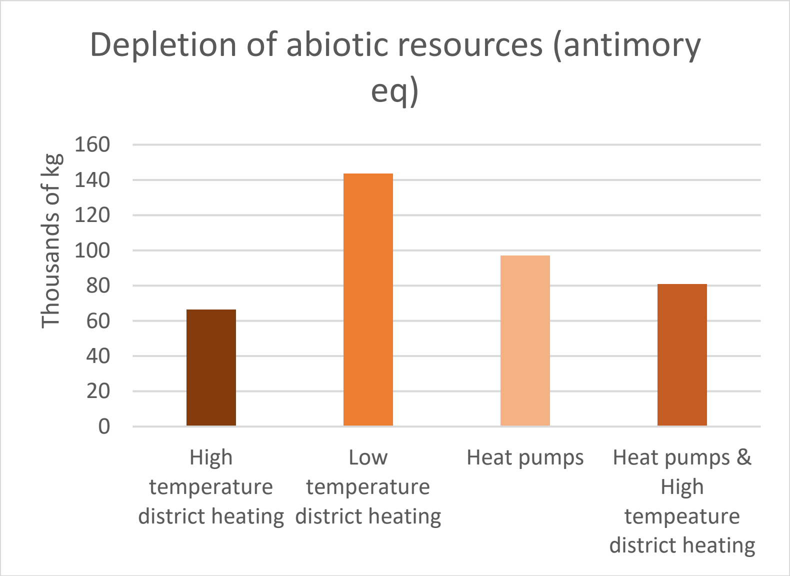


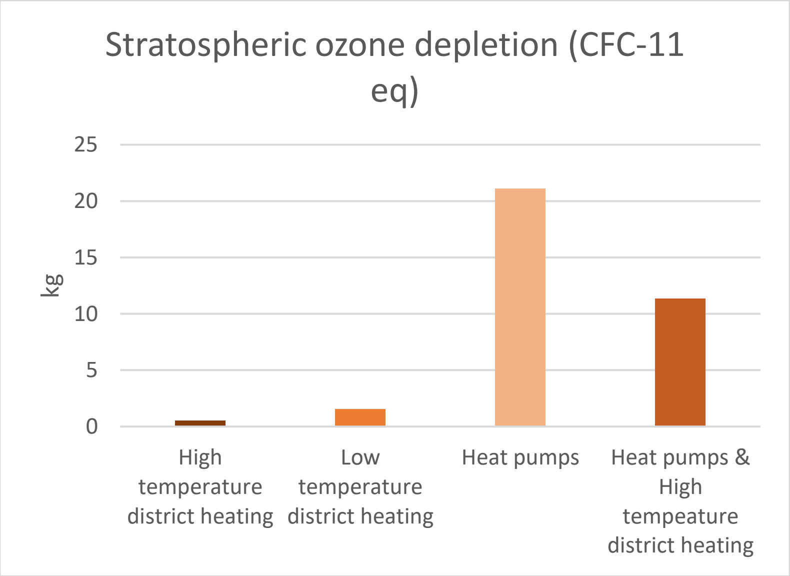












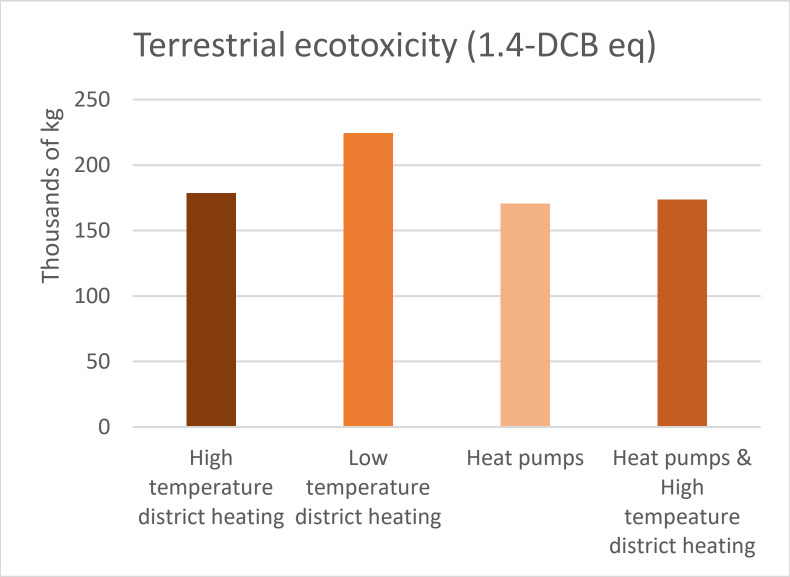


Figure 19 The 9 environmental impact categories for the four different scenarios. The y-axis is in kilograms, thousands of kilograms or millions of kilograms

5.2.1 Stratospheric ozone depletion

In the stratospheric ozone depletion categorie the heat pumps stand out with 21.1 kilograms of CFC-11 (eq). The combined scenario is the second largest with 11.4 kilograms of CFC-11 (eq), where both scenarios in district heating have an impact of 0.5 and 1.6 kilograms. When we zoom in on the stratospheric ozone depletion bar chart and break the heat pumps down in terms of material contribution (Figure 20), it can be seen in that the significant difference between the scenarios is caused by the refrigirant R-134a, that contributes to more than 90% to the stratospheric ozone depletion.

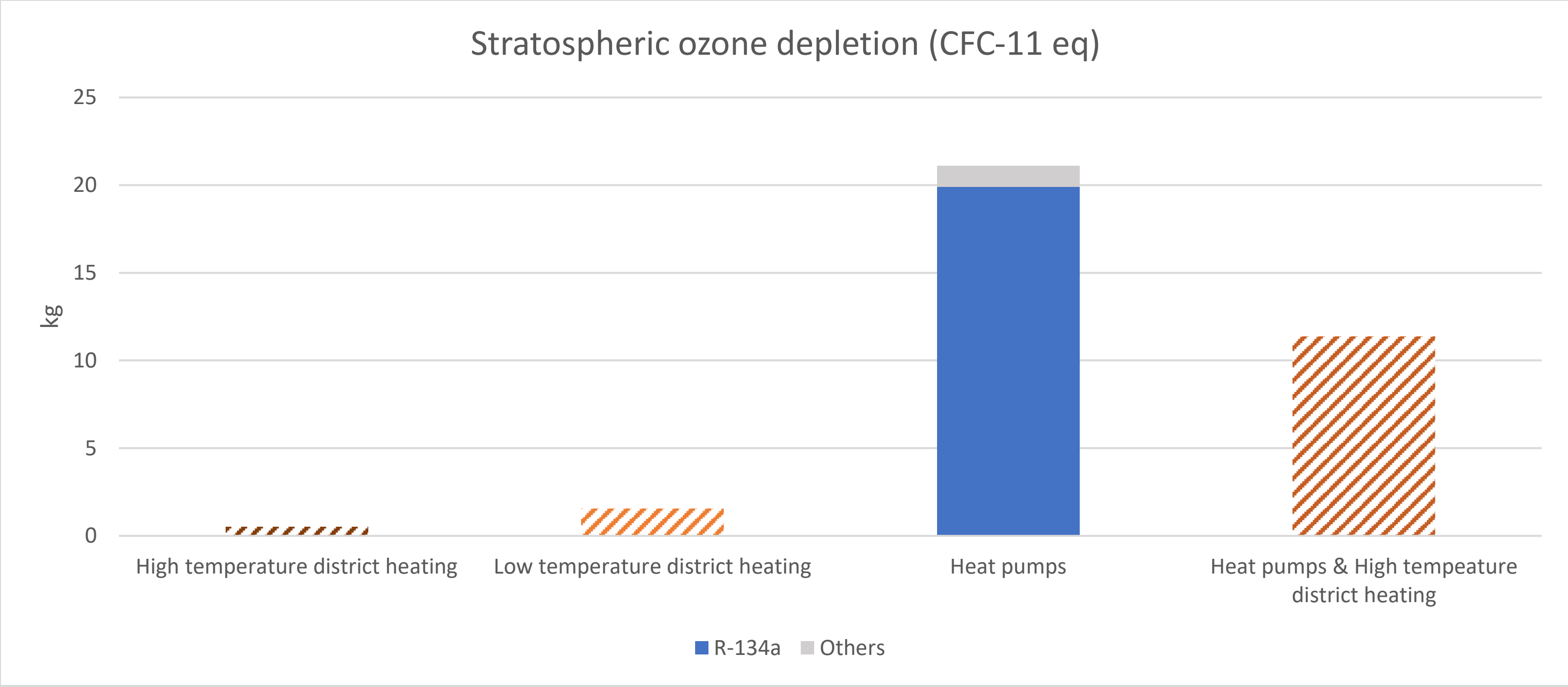


Figure 20 Stratospheric ozone depletion impact of the required materials for the heat pump scenario

5.2.2 Terrestrial ecotoxicity

In the terrestrial ecotoxicity the impact of the high temperature district heating scenario is relativly high compared to the other scenarios and environmental impact categories. In the terrestrial ecotoxicity the high temperature district heating scores second highest with around 180,000 kilogram of 1.4-DCB (eq). The low temperature scenario scores in this impact categorie the highest with around 225,000 kilograms of 1.4-DCB (eq). Heat pumps on the other hand score just slightly lower than the high temperature district heating scenario in contrast to the other impact categories, where the heat pumps score significantly higher than the high temperature district heating scenario. Looking further into the material contribution to the terrestrial ecotoxicity for both the heat pump scenario and the high temperature district heating scenario brings to light that less amount of copper is needed in the high temperature district heating scenario, a significant larger amount of steel is used in this scenario and unlike the heat pump scenario, cast iron is used in the high temperature district heat network scenario (Figure 21). However, copper has more than ten times the impact on the terretrial ecotoxicity when compared with steel and cast iron per kilogram of material (Excel: Technologies). Nevertheless, the high temperature district heat network scenario scores higher than the heat pumps due to the large amount of cast iron and steel that is used in this scenario.

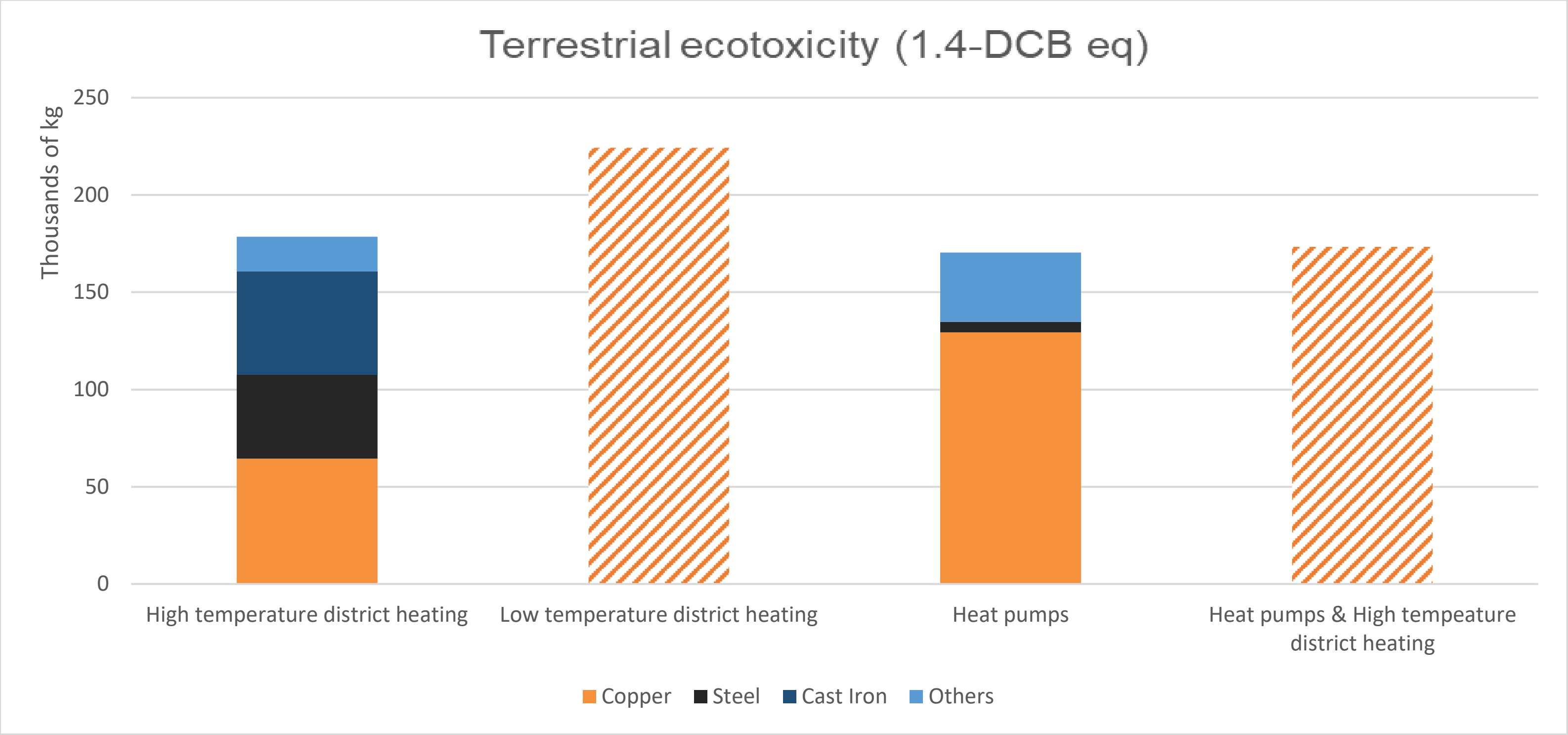


Figure 21 Terrestrial ecotoxicity impact of the required materials for the high temperature district heating and heat pump scenario

5.2.3 Climate change

The main environmental impact focus of the Dutch government and in this thesis, is on the climate change impact measured in CO_2 (eq). Looking at the scenarios the same trend can be perceived as previously mentioned in 5.2 (from high to low): LTDH, HTDH, combined scenario and heat pump scenario. To look what causes this pattern in the climate change impact categorie and to look at what the main material contributors are to the climate change impact in every scenario, the contribution of the materials is presented in Figure 22.

The HTDH scenario has a climate change impact of 9.9 million kilogram of CO_2 and has the lowest impact of the four scenarios. Approximatelly 60% of their impact is caused by ceramic bricks (24%), steel (21%) and cast iron (15%) that are used in surface boxes, water pumps and the pipelines, that are all technology related.

In contrast to the HTDH scenario, the LTDH scenario has the highest impact of the four scenarios with approximately 21.4 million kilograms of CO_2 (eq). The difference with the HTDH is that the LTDH requires insulation. This is also the main contributer to the climate change impact with respectively 45% of the total impact, caused by glass (23%) and glass wool (23%).

The heat pump scenario requires the same amount of insulation, since both the technologies deliver low temperature heat. However, the impact on the climate change in terms of CO_2 (eq) is lower than the LTDH scenario, 14.3 million kilograms versus 21.4 million kilograms. That means that the impact of the heat pump technology on climate change is 35% lower than the district heat network. In this scenario the insulation counts for almost 70% of the total climate change impact.

The combined scenario is in between the HTDH scenario and the heat pump scenario with a climate change impact of 12 million kilograms of CO_2 (eq). In this scenario the insulation materials, glass (21%) and glass wool (21%) contribute to almost 40% of the total climate change impact.

Overall in the scenarios where low temperature heating is involved the insulation materials contribute for approximately 50% to the climate change impact. That could mean there is a great potential in closing the loop as much as possible for glass and glass wool in order to lower the environmental impact significantly. For the high temperature alternative the metals cast iron and steel, and the ceramic bricks are responsibe for a little bit more than 50%. Closing the loop for these materials could also be solution to significantly lower the climate change impact.

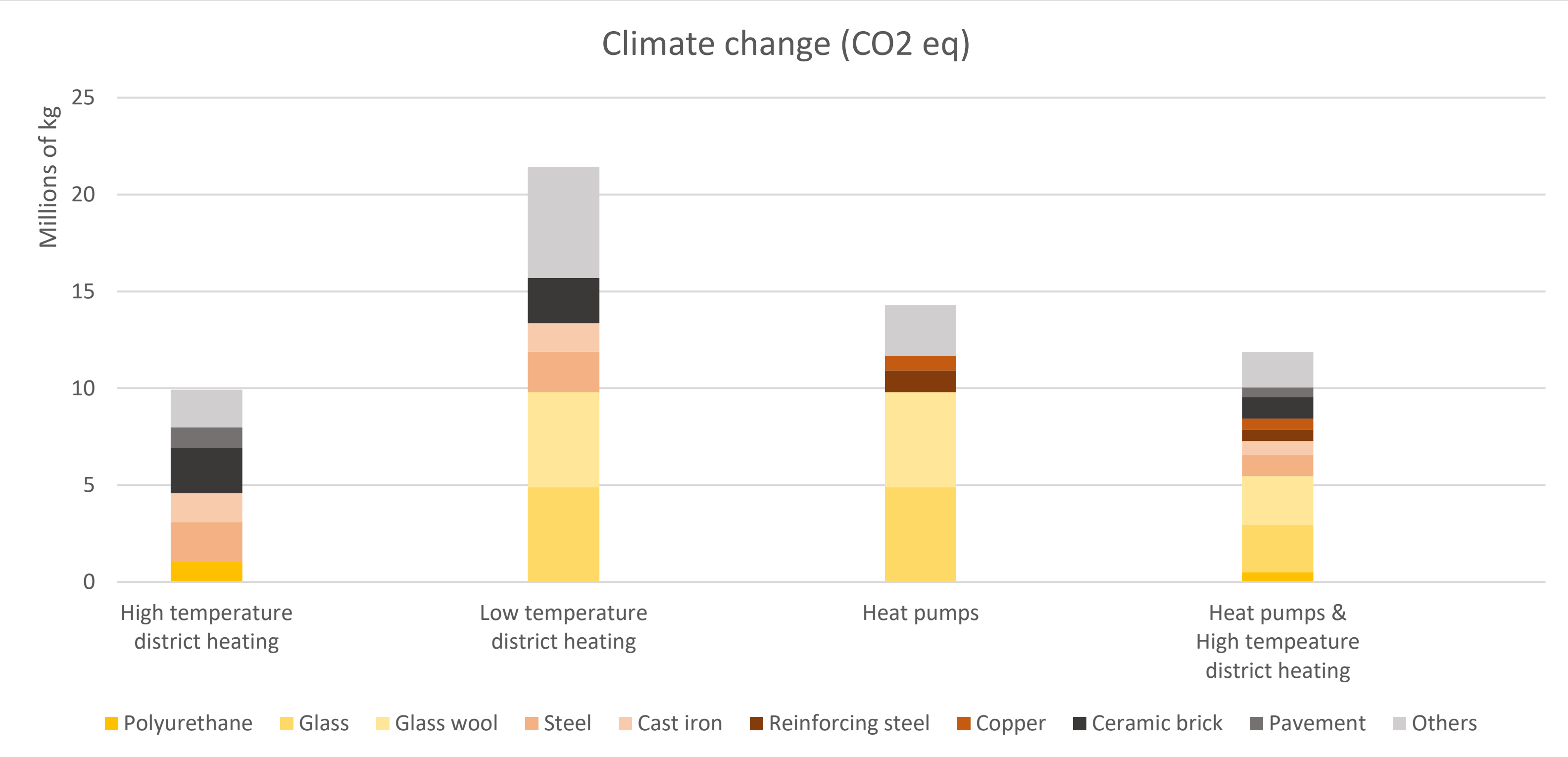


Figure 22 Climate change impact of the required materials in kilogram CO2 (eq) for the four scenarios

Figure 23 shows what the climate change impact would look like on building level in the Merenwijk for the four different scenarios. The maps show that the more dwellings per building, the higher the climate change impact is. They also show that for the low temperature alternatives, the larger and older the buildings are, the higher the impact is. The older the higher impact, is due to the lower insulation values of the older buildings and to meet the minimal insulation requirements more insulation material will be needed. The bigger the building, the bigger the impact, due to the larger areas that need to be insulated and the more windows that need to be replaced.

Figure 23 Four maps that presents the kilograms of CO2 (eq) for the required materials for all four scenarios in the Merenwijk on residential building level

5.3 Leiden

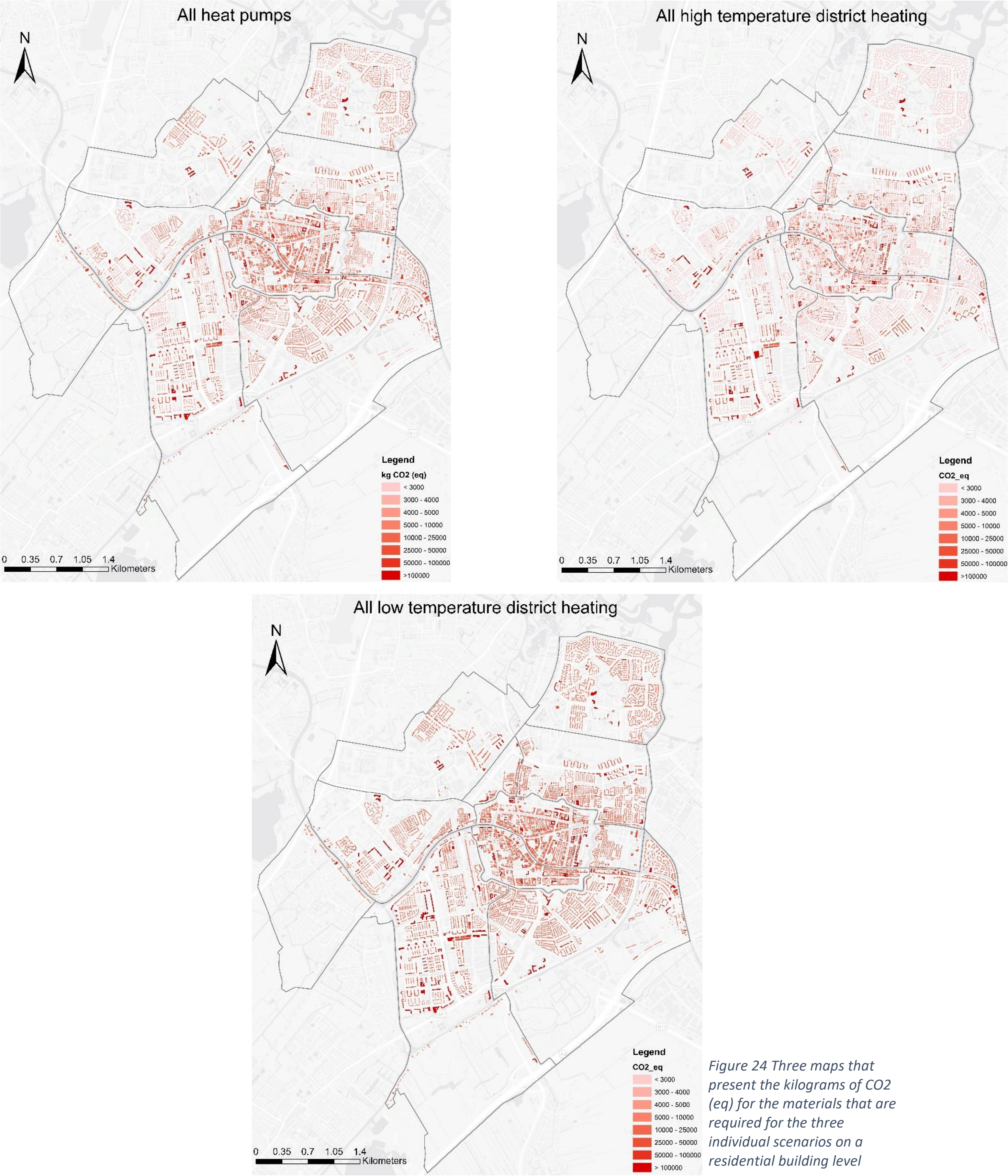


Figure 24 Three maps that present the kilograms of CO2 (eq) for the materials that are required for the three individual scenarios on a residential building level

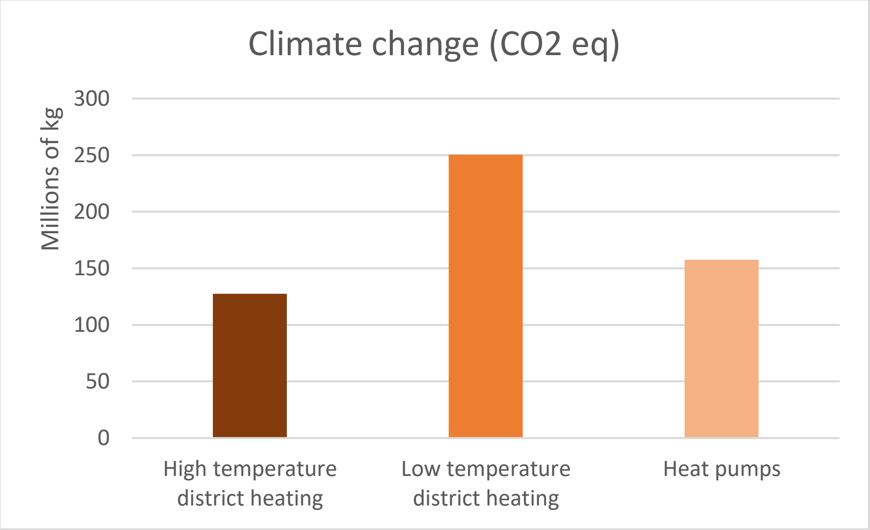


Figure 25 Total amount in kilograms CO2 (eq) for the required materials for all three scenarios in Leiden

To test if the model also works on a larger scale, the geographical boundaries were extrapolated to Leiden and three maps were created for the three alternative more sustainable technologies. In the maps (Figure 24) it can be seen that for the two low temperature heating scenarios the city center is darker red than the surrounding districts. The relative difference between all three scenarios, Figure 25, corresponds to the relative difference that can be seen in Figure 19.

In the Leiden model there are 25894 buildings and 46218 dwellings. In the Merenwijk model there are 3691 buildings and 4176 dwellings. In Figure 27 & Figure 26 the differences between both scenarios for CO2 (eq) per building and per dwelling is presented. Per building the Merenwijk has a much lower climate change impact than the average in Leiden. However, when looking at the average impacts per dwelling for both scales the Merenwijk scores slightly higher in the heat pump and low temperature district heating scenarios. The high temperature district heating has the same impact in both scenarios, because the material requirements are calculated per dwelling. The difference between the outcomes looking at per dwelling and per building is caused by the average amount of dwellings per building. The average amount is higher in the Merenwijk than in the rest of Leiden. However, it must be said that for the input of the material calculations for the district heat network scenarios in Leiden, the building and dwelling density of the Merenwijk is used. In future research the density of the buildings should be easily adjustable in the GIS model by implementing the building and dwelling density calculations directly into the model.

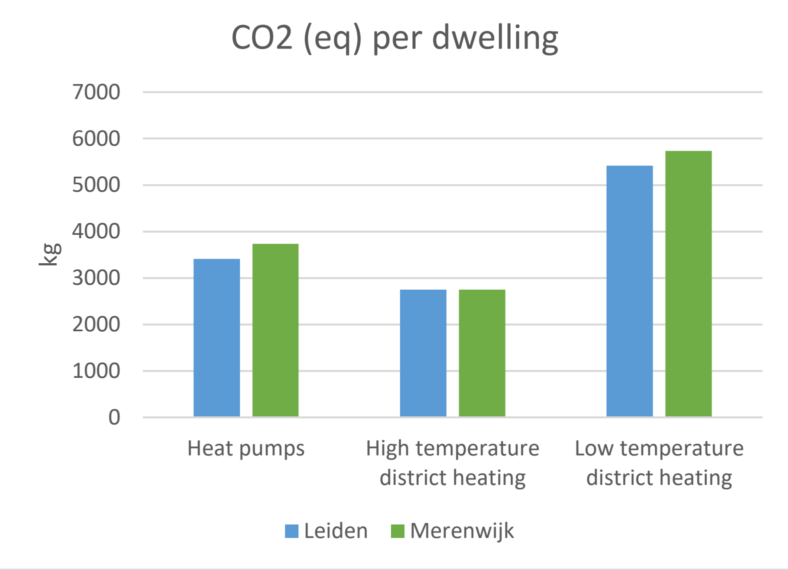


Figure 27 Kilograms CO2 (eq) per dwelling

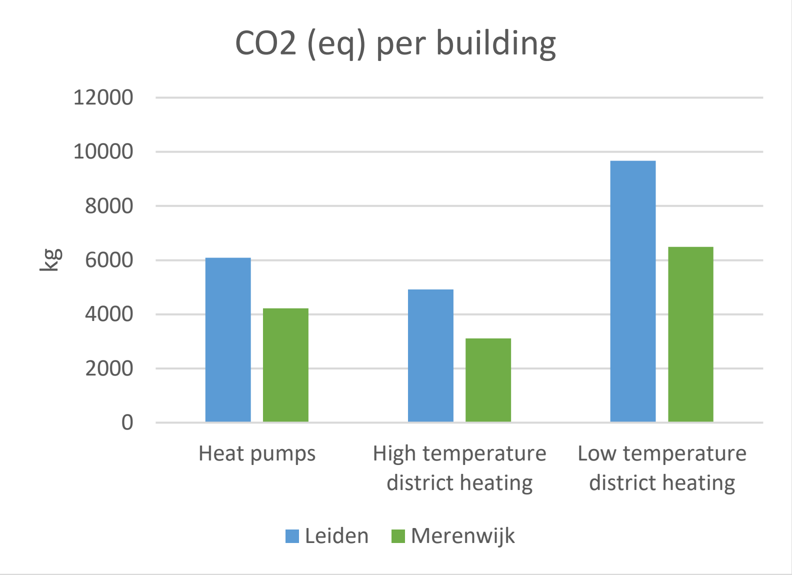


Figure 26 Kilograms CO2 (eq) per building

6. Sensitivity analysis

The material data that is used in this thesis is partially based on indirect sources and assumptions. Also the scenarios used in this thesis along with the results are mainly theoretical. In reality it will most likely be a combination of all sorts of scenarios. In order to act on this and to test the validity of the sources and assumptions used in this thesis, the input parameters were increased and decreased by 10%. In this way the parameters with the highest sensitivity will be identified. It is important that the accuracy of these parameters is as high as possible and further research may be required to improve the accuracy of these parameters. In this analysis I will look at the sensitivity of the climate change impact results and the glass wool demand when changing some of the input parameters.

In Figure 28 & 29 the results of the sensitivity analysis on the climate change impact can be seen. The results show that the 10% change in dwelling density (3.98% / -3.26%) results in the highest percentual change of all input parameters in all the district heat scenarios, followed by the height of the buildings (-3.17% / 3.17%) and the minimal Rc value for the implementation of low temperature heat technologies (-2.95% / 2.95%). For the heat pump scenario, the 10% change in the height of buildings (-4.99% / 4.99%) shows the biggest change on the climate change of all parameters. This input parameter is followed by the minimal Rc value for the implementation of low temperature heat technologies (-4.64% / 4.64%) and the floor area (-4.37% / 4.37%).

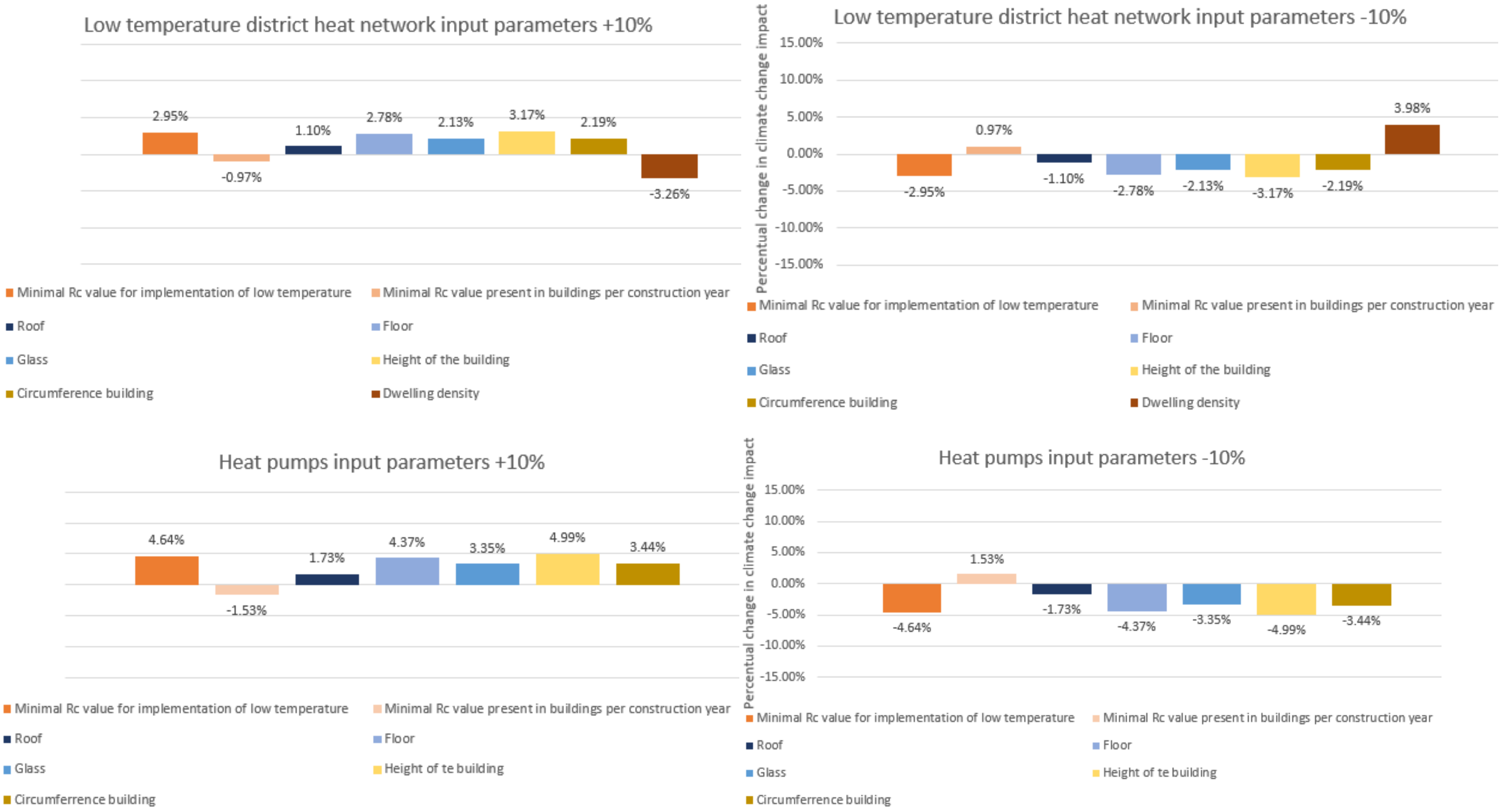


Figure 28 Sensitivity analysis of the two low temperature scenarios. In this analysis the change in climate change impact is measured by increasing and decreasing the input parameters (see legend) by 10%.

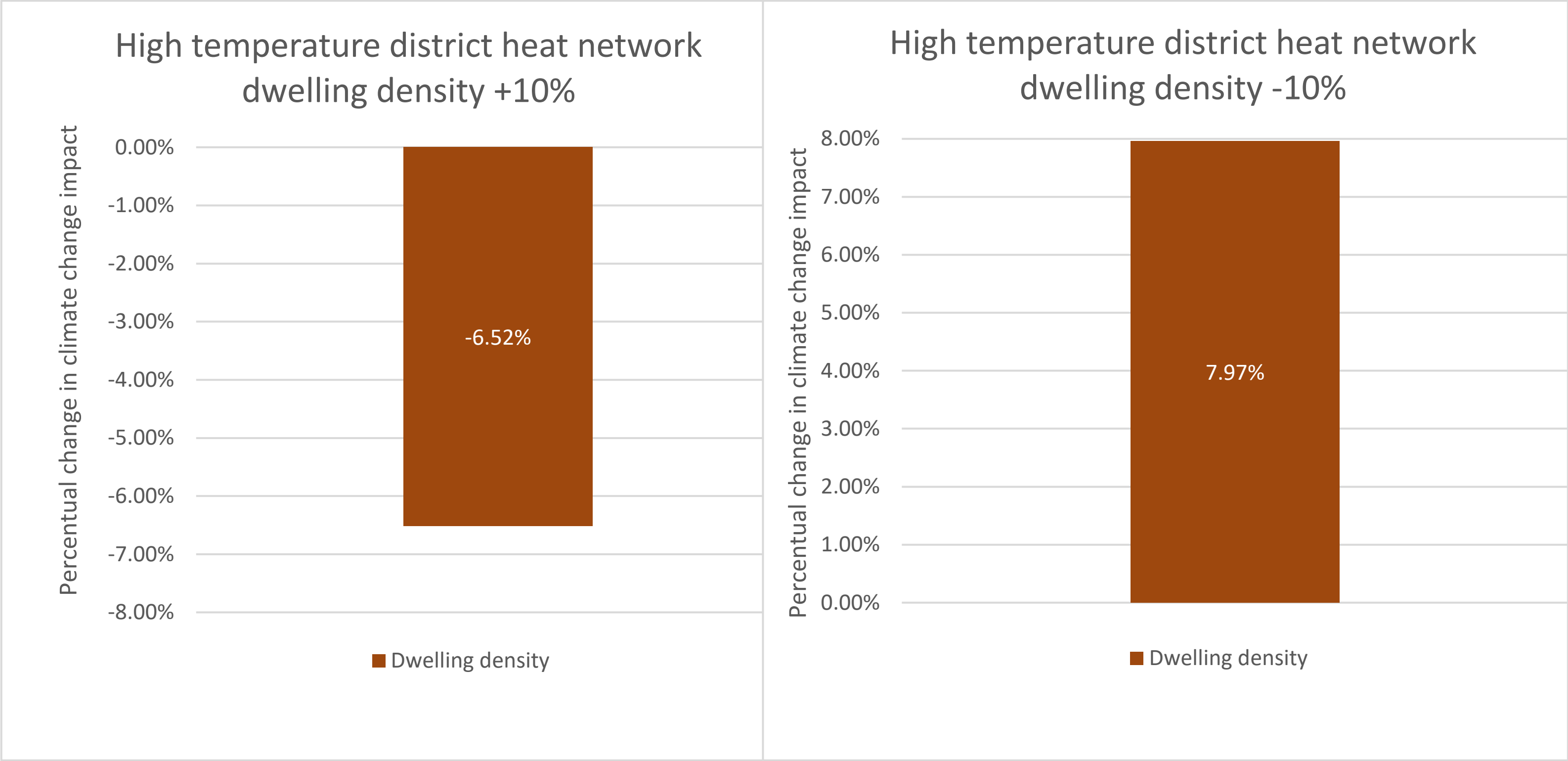


Figure 29 Sensitivity analysis of the high temperature district heating scenario. In this analysis the change in climate change impact is measured by increasing and decreasing the dwelling density by 10%

In Figure 30 the sensitivity of the input parameters is shown for the glass wool demands. The Minimal Rc value for the implementation of low temperature technologies is by far the most sensitive parameter. With the increase and decrease of 10% in minimal Rc value the glass wool demand increases or decreases by more than 10%. In the low temperature scenario, the glass wool demand changes by -13.84% / 13.84 %. Since both low temperature scenarios need the same requirements in terms of insulation the results will be the same. The second most sensitive parameter is the floor area parameter. Changing the floor area by 10% would mean a change of 9.37% in glass wool demand.

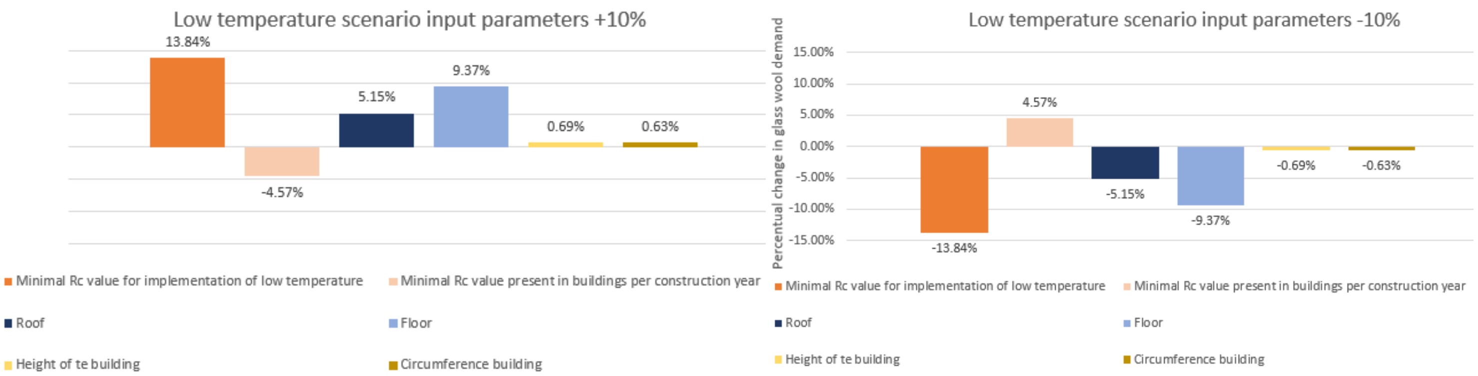


Figure 30 Sensitivity analysis of the low temperature scenarios. In this analysis the change in glass wool demand is measured by increasing and decreasing the input parameters (see legend) by 10%. For the glass wool demand the low temperature district heat network scenario is equal to the heat pump scenario.

6.1 Dwelling density

In this thesis the dwelling density per 100 meter of pipeline is calculated by using the total amount of dwellings and the total amount of meters of gas pipeline inside the Merenwijk. I had to assume that the gas network is representative for the heat network in terms of length. The calculations are manually done and implemented into the model. This is therefore the only parameter in the model that is not dynamic and generic yet. In order to use the model for other locations an additional formula should be implemented in the GIS model in order to make the dwelling density and thus the calculations for the materials inside the district heat network generic and dynamic. This would make the model more robust and the results more realistic. The factor that could have a significant impact on the results is the assumption that the heat network would be equal to the current natural gas network.

6.2 Rc value for the implementation of low temperature heat technologies

The minimal Rc value for the implementation of low temperature heat technologies is in all cases the most sensitive input parameter on both the climate change impact and the glass wool demand. The minimal Rc value is used for the calculations on the insulation demand (glass wool) inside the residential buildings. Increasing the minimal Rc value that would be needed for the implementation of low temperature heat technologies, would also mean an increase in insulation that is needed to meet the new requirements. The requirements in this thesis are based on the last flyer from *woonwijzerwinkel* (Appendix 1) and the expert judgement from Sabine Jansen. The flyers from the *woonwijzerwinkel* are a good indicator of the Rc values that are needed and already present in residential buildings. But these are just indicators and not proven or researched yet. However, with the help of an expert the data on the minimal Rc value became more reliable.

6.3 Building height

Climate change impact reacts sensitive to a change in building height. However, glass wool does not seem to react sensitive on a change in building height. The difference in sensitivity for building height can be explained using building height in the model. For the calculations on glass wool the building height is only used for the wall area calculations and this is just a fraction of the entire glass wool demand calculations. For the calculations on climate change impact however, the building height is not only used for the wall area calculations, but also for the volume calculations that are needed for the heat emission systems and the ventilation systems. The building height is gathered from the BAG3D data that is created by *het kadaster.* They gather data on buildings and areas for decades and are quite accurate. However, there is a constant change in building composition, so to keep the data up to date is challenging. It is also maintained by hand and that is when data mistakes can be made.

6.4 Floor area

One of the most sensitive parameters for both the climate change impact and the glass wool demand is the floor area. The data of the floor area is based on automatic calculations by ArcGIS, where the shape area of a polygon is automatically measured. That does not mean there is no error margin, but it is more reliable than the indirect data that is gathered from papers or based on own estimations. However, the relatively high sensitivity is mainly caused by the calculations on the area. The roof area is calculated by using the Shape_area (floor area). Changing the Shape_Area by 10% means that also the roof area will change by 10%.

Of the 4 most sensitive parameters, the building height and floor area are the most reliable data used in this model. The two most sensitive parameters (Rc value for the implementation of low temperature heat technologies & building density) however, are also the parameters where multiple assumptions are made and the reliability of the data could be questionable. But with the data that was available for these parameters, the most realistic and reliable sources are used.

7. Discussion and Conclusion

7.1 Discussion

In order to reach the climate neutral and circular economy goal by 2050 the Netherlands needs to make some radical changes in several sectors. One of most important sectors for the climate neutral goal is the heating of residential buildings. For new built residential buildings the changes have already begun. However, it looks like the heat transition in the current building stock is overlooked by most governmental organisations and misjudged by the organisations that have looked into it. Their focus is on making the transition fast and easy, rather than sustainable.
Current literature is not sufficient to assist these governmental organisations. It is too focussed on specific elements of the heat transition, while the entire transition is far more complex and important.

The main focus of this thesis is on the demand for materials in the heat transition and the environmental impacts of these materials from cradle to market. This focus was applied to the Merenwijk in order to show its impact. Because the future of sustainable heat alternatives is still not known yet, four different transition scenarios were studied: All heat pumps, all high temperature district heating, all low temperature district heating and a combination of heat pumps and high temperature district heating. Per scenario the materials and their environmental impact were calculated by combining different LCI's with spatial data layers. This combination of LCI/LCA and GIS is relatively new and gave meaningful insights on the environmental impacts of the heat transition scenarios in the Merenwijk. The strength of the thesis is the dynamic model that is created. The model uses open spatial data on Dutch scale level and implements the LCI's I retrieved from previous papers. The results of the model gave supplementary information on the climate neutral goal of Leiden, but because the BAG_3D spatial data layer is uniform for the whole Netherlands, it is also possible to run the model on other places within the Netherlands.

In the first part of this thesis the material requirements were calculated for the four different scenarios. For the scenarios with the district heat technology as an alternative, a significant amount of materials was needed for the trench works and surface boxes. This mainly consisted of ceramic bricks, concrete (others), sand and aggregates (trench backfilling materials). These materials have been widely used for centuries in the construction sector and would not have a significant impact on the global and national market. For example, extrapolating the heat transition and its demand for concrete the Merenwijk to the Netherlands, would have an impact on the yearly global market for less than 0.1% (Grand view research, 2018).

However, the demands that would have a significant impact on both the national and global market are the demands for glass and glass wool used in the low temperature scenarios. Extrapolating the material demands from the Merenwijk to the Netherlands would give a total demand of 9.9 billion kilograms of glass and 3.3 billion kilograms of glass wool. To put this into perspective, in the Dutch glass market of 2016 there was a total sale of 4.6 million m^2 for the existing building stock, that is equal to approximately 72 million kilograms of glass (RVO, 2018). This would mean that it would take 137 years to deliver the amount of glass in the current Dutch glass market. In the Dutch organic wool market of 2016 there was a total sale of 13.9 million m^2, that is equal to approximately 27.8 million kilograms. This would take 120 years to cover the demand for glass wool in current market. However there are only 31 years left. That would mean that when the transition would start today the current glass and glass wool market should be at least 4 to 5 times bigger to cope with the demand and would increase each year when nothing will happen. Even on the global market the demand for glass wool in the low temperature scenarios would have a significant impact. The global market is expected to grow to 5 billion kilograms of sales on an annual basis (Global Market Insights, 2016). That would mean that roughly 2% of the glass wool market will be dominated by the demand from the Netherlands on an annual basis for the next 31 years. On top of that, there is also an increasing demand from the dominant construction industries of China and the United states that is growing with a pace of 5% annually. And we should not forget the upcoming economies like India, that will most likely join the top 3 largest construction markets in the coming years (Markets Insider, 2018). This global growth in combination with the 2% yearly demand pressure on the global market by the Netherlands could lead to scarcity, increasing prices and dependency on other regions. Therefore similar studies like the study by Sprecher et al. (2014) should be done on the recycling potential of certain materials, in order to find opportunities to close the loop and lower the demand for materials and their environmental impact. There must be said that in this thesis glass wool is chosen as the only insulation material. In reality multiple insulation materials will be used, like stone wool and aluminium bubbles and the demand will be spread over multiple insulation materials.

In the heat transition for the Netherlands there are several opportunities to recycle the waste flows of future end of life products and to recycle or reuse the materials that can be recovered from the current natural gas system. An example of such an opportunity is the replacement of the glass windows for the low temperature scenarios. The replaced glass could be recycled and used as a source for the production process of glass wool (Isover, n.d.). This could not only lower the demand for materials and the dependency on other regions, but could also have environmental benefits from the embodied emissions inside these materials. However, in future studies the real feasibility of recycling and reusing different material flows has to be studied.

In the second part of the thesis I focussed on the environmental impact of the used materials for the different scenarios in the heat transition. The main focus was on the climate change impact, in order to look at the impact the materials would have on the climate neutral goal. The model showed that for the Merenwijk district there is a significant difference between the environmental impact of the required materials in the low and high temperature scenarios. The climate change impact of the materials used in the low temperature scenarios are for more than 40% caused by insulation materials: glass and glass wool. In the high temperature scenario there are no insulation materials required. Therefore, materials used in the technology account for all the climate change impact. 50% of the climate change impact in this scenario is caused by ceramic bricks, steel and cast iron.

This corresponds with a study done by Fröling et al. (2004), which also concluded that the steel, mainly used in the network pipelines, is one of the main contributors to the climate change. However, there are also some difference between the findings of this thesis and their paper. The main difference is that their main contributors are not only steel, but also the use of asphalt and an excavator. The use of asphalt and the excavator are not in the scope of this thesis. The use of asphalt is left out because most heat district pipelines will be put under pavements instead of asphalt roads in the Netherlands. The use of excavators is not included, because the thesis focusses on the environmental impact of materials from cradle to market and the use of excavators is in the implementation phase. This also accounts for the manhours and diesel used for the excavator that are not included. However, it could be interesting to extend the researched lifecycle and include the implementation phase in further research to further explore specific scenarios. Fröling on the other hand did not include the surface boxes and pumps for the main grid in his environmental impact calculations.

The total climate change impact in the Merenwijk for the four scenarios is: 14.6 million kilograms CO_2 (eq) for the heat pump scenario, 11.5 million kilograms CO_2 (eq) for the high temperature district heating scenario, 23 million kilograms CO_2 (eq) for the low temperature district heating scenario and 12.9 million kilograms CO2 (eq) in the combined scenario of heat pumps and high temperature district heating.

To put these results into perspective, I compared the results to other environmental calculations and to current market figures of the most demanded materials. Verhagen (2018) concluded that the heat pump scenario, compared to the original natural gas heat system, has a yearly CO_2 reduction of 6.8 million kilograms. Considering a heat pump's lifetime of 20 years would mean that there would be a reduction of 130.6 million kilograms in CO_2 emissions. In addition to his results this thesis shows that the materials used in the heat pump scenarios have an impact of 14.6 million kilograms of CO_2 (eq). That means that the indirect environmental impact of the materials will reduce the total reduction in the heat pump scenario by approximately 10% and will be covered in the first 2 years of operation. However, to make the more sustainable scenarios comparable to the current situation of the heat system (natural gas), the impact of the renewal of the end of life products of both the current situation and the more sustainable alternatives should be included.

In addition to the climate change impact, there are other environmental impacts contained inside the materials which might play a role in decision making in the future. In my thesis I did not only use the climate change impact to compare the different scenarios, but I also used: acidification potential (SO2-eq), climate change (CO2-eq), eutrophication potential (PO4-eq), freshwater aquatic ecotoxicity (1,4-DCB-eq), human toxicity (1,4-DCB-eq), photochemical oxidation (ethylene-eq), depletion of abiotic resources (antimony-eq), stratospheric ozone depletion (CFC-11-eq) and terrestrial ecotoxicity (1,4-DCB-eq).
The high temperature district heating scores the best in 8 out of 9 environmental impact categories. Therefore they may look like the best sustainable heat technology, because they not only score almost better in all environmental impact categories, but are also easier and faster to implement and cost less materials. However, they are considerably less efficient than the low temperature technologies during their lifespan and would have a higher impact on the climate change, than the low temperature alternatives. Therefore, the positive results in this research do not cover the whole environmental impact of the high temperature district heating network, but only a small part of the total impact. A suggestion for further research would be to combine the different impact parts and calculate the total environmental impact.
The low temperature district heating scenario scores the worst of all scenarios in 6 out of 9 impact categories. That means that the materials used in the heat pumps on average have a lower impact on the environment, than the materials in the district heat network, because the required insulation materials are equal in both scenarios. Only for stratospheric ozone depletion the heat pump scores considerably worse than all other scenarios. This is due to the refrigerator that is used inside the heat pumps. The high impact on the stratospheric ozone depletion was also concluded in a report by Rey et al. (2004). He concluded that the refrigerator contributed 40% to the stratospheric ozone depletion. In my thesis however, it contributed almost 95% to the stratospheric ozone depletion. There are two explanations for this difference. First, the difference in refrigerators used in both studies. In the report by Rey et al. (2004) the refrigerator R22 is used, while in this thesis the refrigerator R-134a is used. Second, in the report by Rey et al. (2004) an air-air heat pump was used, while in this thesis an air-water heat pump was used. However, on the refrigerator R-134a is a production restriction in the Netherlands in order to let producers search for more environmental friendly alternatives like CO_2, propane or ammoniac. The data on these type of heat pumps is very limited and therefore not taken into account in this thesis, but should be considered in future studies.
The heat pumps score for 5 out of 9 environmental impact categories in between the low and high temperature district heating. 3 out of the 4 other environmental impact (fresh aquatic ecotoxicity,

human toxicity, stratospheric ozone depletion) categories the heat pumps score just a little bit worse than the low temperature district heating scenario and scores therefore the worst of all scenarios. The heat pumps scenario scores worse because of the high impact of copper on both categories and the higher demand of copper in the heat pump scenario. The stratospheric ozone depletion impact is caused by the refrigerator that is used inside the heat pumps. The other remaining environmental impact category, terrestrial ecotoxicity, the heat pumps scores best on impact. This is caused by the higher amount of steel, copper and cast iron that is required by the district heat network.

7.2 Limitations and future research

There are potentially several important drawbacks associated with my thesis. Some of these limitations are already addressed in the above paragraphs. The foremost limitation of this study is the scope of the lifecycle of the technologies. In my thesis I chose to do the cradle to market part of the lifecycle. This means that the production phase and end of life phase of the technology is not included. Research on the recycling potential for all technologies, products and materials used in the heat transition would be of great value for the accuracy of the estimations made in my thesis. Recycled materials for example might have a lower impact on the environment than the virgin materials have. The success rate of the results in my thesis compared to a detailed LCA is approximately 67% and still good enough to provide a good overview on the different scenarios with the environmental impact of the materials used (Rebitzer, et al., 2004). In addition to this, there was also no other choice, because the data on the end of life options is very limited and inaccurate. This limitation will be lifted when more data becomes available as time progresses. So in a few years another study may be able to combine the model in this thesis with data on the end of life options.

The model that is created is not dynamic for every scenario. For the district heat network and the current natural gas network, there was limited data available on the materials used. The best data was by Oliver-Solà et al. (2009a & b) on the materials for the district heat network. However, his results were calculated by using a low and high dense area. In my thesis model I recalculated it to the density of the Merenwijk. That means that it would perfectly fit for the material demand in the Merenwijk, but using it on a larger scale would still measure the material demand for the density of the Merenwijk. To solve this problem, additional steps should be added in the Model builder in ArcGIS in order to measure the density in a given area and multiply this by the materials that would be needed by the district heat network. In current model this formula has to be implemented for each individual material that is used in the district heat network. Also, the natural gas network is not implemented in the model builder of ArcGIS. All calculations are done manually in excel. In further research the natural gas network should be implemented in the model builder in order to make it an automatic model, where only ArcGIS is used to present and produce results. Additional futures could be added as well. An example of such a future could be on how much glass would become available when low temperature alternative technologies are implemented.

The Dutch government obliges that tap water should be heated to at least 60 degrees Celsius in order to prevent legionella. This most likely means that an additional technology is required in the low temperature scenarios. For both the low temperature technologies considered in this paper it was not clear whether the heating of tap water was included in the material inventory. Therefore additional research is required to make sure that the heating of tap water is also included in the material inventory, conform to the Dutch standards.

Another drawback that I encountered during my thesis was, that the material data on the radiator ventilators, air vents and mechanical ventilation box was very limited. Therefore, I chose to look at data from similar peripherals, in order to make realistic estimations on the used materials inside these peripherals. To make these calculations more accurate, research should be done at the production side of these peripherals. Because the data most likely exists, but might not be publicly available for competitive reasons.

A sensitivity analysis on the model showed that building height, floor area, Rc value for the implementation of low temperature technologies and building density are the most sensitive parameters. Of these 4 parameters, the building height and floor area are the most reliable data used in this model. The two most sensitive parameters (Rc value for the implementation of low temperature heat technologies and building density) however, are also the parameters where multiple assumptions are made and the reliability of the data could be questionable. Therefore, in order to improve the accuracy of the model, further research should be done to improve the quality of the data on the Rc value for the implementation of low temperature heat technologies and building density.

In this thesis there are four scenarios used with three different technologies as a solution for the heat transition in the Netherlands. I chose these technologies based on available data and their occurrence in existing plans. In the future the heat transition will not only be completed by using these three technologies, but also by using other already existing or innovative technologies. Therefore, research on this topic needs to be improved and extended in order to make calculations and scenarios on the heat transition more realistic and ambitious.

Other recommendations for future studies would be to include other types of data inside the model. An example would be to include fuel savings of the different technologies in every individual building. When including the other data inside the model, the model could be improved as well to make it more efficient and easier to run. An example would be to create separate models for the different steps that are used and make a clean script in python, instead of directly using the ArcGIS model builder. This would not only make the model faster to run, but would also improve the functionality of the model, because it could be connected to other models as well. In Appendix 6 these model improvements are discussed more into detail.

7.3 Conclusion

In the end the results of this thesis are an addition to current research on the fuel savings of the sustainable heat technologies. Looking at the material requirements for all scenarios a problem seems to arise when the low temperature scenarios will be implemented. Not only does the Dutch insulation market not look prepared, but also the global market. These scenarios will cause the Dutch demand for glass wool to rise to more than 2% of the global market. The Dutch insulation market does not seem to be prepared for such an increase in demand. And with global demand for glass wool already rising, it is uncertain if the increased demand can be met.

This study provides a solid basis for the environmental impacts for the heat technologies and their peripherals, especially for the heat transition in the Netherlands. The general understanding in the field of environmental studies is that the environmental impacts are calculated by the savings in fuel used in the different technologies. This thesis provides an addition to current environmental calculations by looking at the material environmental impact in an upcoming large-scale heat transition. The environmental impact of materials does have a significant impact on overall environmental calculations.

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Apendix

Appendix 1

Bouwjaar: voor 1930

In deze bouwperiode werden er nog geen eisen gesteld aan de energiezuinigheid van woningen en er werd ook nog geen spouwmuur toegepast.

Een groot deel van deze woningen is energetisch verbeterd. Zij zijn voorzien van centrale verwarming met een HR combiketel, dubbelglas en kierdichting. Na-isolatie van de dichte geveldelen blijft sterk achter.

Eigenschappen

- Ongeïsoleerde houten vloer
- Steensmuren zonder spouw
- Ongeïsoleerde dak
- Natuurlijke ventilatie
- CV niet altijd aanwezig
- Enkel- of dubbelglas
- Geschat energielabel: G

Hoe kom ik op label B of hoger?

Bouwjaar: 1930 tot 1945

In deze bouwperiode werden er nog geen eisen gesteld aan de energiezuinigheid van woningen. Na 1930 werden er spouwmuren toegepast.

Een groot deel van deze woningen is energetisch verbeterd. Zij zijn voorzien van centrale verwarming met een HR combiketel, dubbelglas en kierdichting. Na-isolatie van de dichte geveldelen blijft sterk achter.

Eigenschappen

- Ongeïsoleerde houten vloer
- Ongeïsoleerde spouwmuur
- Ongeïsoleerde dak
- Natuurlijke ventilatie
- CV niet altijd aanwezig
- Enkel- of dubbelglas
- Geschat energielabel: G

Hoe kom ik op label B of hoger?

Bouwjaar: 1946 tot 1964

In deze bouwperiode werden er nog geen eisen gesteld aan de energiezuinigheid van woningen. Opkomst van systeem- / betonbouw.

Een groot deel van deze woningen is energetisch verbeterd. Zij zijn voorzien van centrale verwarming met een HR combiketel, dubbelglas en kierdichting. Na-isolatie van de dichte geveldelen blijft sterk achter.

Eigenschappen

- Ongeïsoleerde hout/betonvloer
- Ongeïsoleerde spouwmuur
- Ongeïsoleerde dak
- Natuurlijke ventilatie
- CV niet altijd aanwezig
- Enkel- of dubbelglas
- Geschat energielabel: G F

Hoe kom ik op label B of hoger?

Meer weten? Kijk op woonwijzerwinkel.nl of bel 010 747 01 47

Bouwjaar: 1965 tot 1974

In deze bouwperiode werden er voor het eerst eisen gesteld aan de energiezuinigheid van woningen al waren deze naar huidige maatstaven niet hoog. Centrale verwarming kwam in opmars.

Een groot deel van deze woningen is energetisch verbeterd. Zij zijn voorzien van dubbelglas en kierdichting.

Eigenschappen

- Ongeïsoleerde betonvloer
- Ongeïsoleerde spouwmuur
- Matig geïsoleerd dak
- Natuurlijke ventilatie
- Centrale verwarming
- Enkel- of dubbelglas
- Geschat energielabel: G F E

Hoe kom ik op label B of hoger?

Meer weten? Kijk op woonwijzerwinkel.nl of bel 010 747 01 47

Bouwjaar: 1975 tot 1982

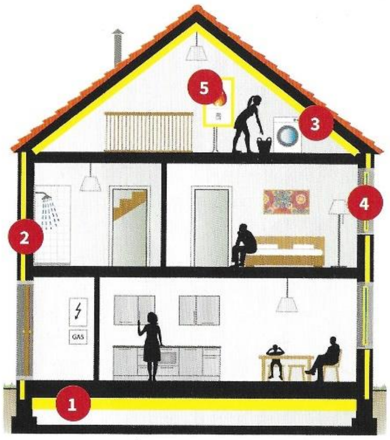
In deze bouwperiode werden er eisen gesteld aan de energiezuinigheid van woningen al waren deze naar huidige maatstaven niet hoog. Vanaf 1975 was de minimale isolatie eis voor dak- en gevel RC = 1,3 m^2K/W.

Het grootste gedeelte van de woningen is voorzien van mechanische ventilatie en HR-combiketel.

Eigenschappen

- Matig geïsoleerde betonvloer
- Matig geïsoleerde spouwmuur
- Matig geïsoleerd dak
- Natuurlijke / mechanische ventilatie
- Centrale verwarming
- Dubbelglas
- Geschat energielabel: D

Hoe kom ik op label B of hoger?



Meer weten? Kijk op woonwijzerwinkel.nl of bel 010 747 01 47

Bouwjaar: 1983 tot 1991

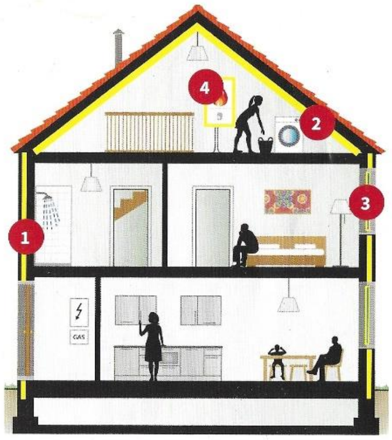
In deze bouwperiode werden er eisen gesteld aan de energiezuinigheid. De woningen zijn voorzien van dak-, gevel- (Vanaf 1983: RC = 1,3 m^2K/W, vanaf 1988: RC = 2,0 m^2K/W) en vloerisolatie (RC = 1,3 m^2K/W).

Het grootste gedeelte van de woningen is voorzien van mechanische ventilatie en HR-combiketel.

Eigenschappen

- Redelijk geïsoleerde betonvloer
- Redelijk geïsoleerde spouwmuur
- Matig geïsoleerd dak
- Mechanische ventilatie
- Centrale verwarming
- Dubbelglas
- Geschat energielabel: C

Hoe kom ik op label B of hoger?



Meer weten? Kijk op woonwijzerwinkel.nl of bel 010 747 01 47

Bouwjaar: 1992 tot 2005

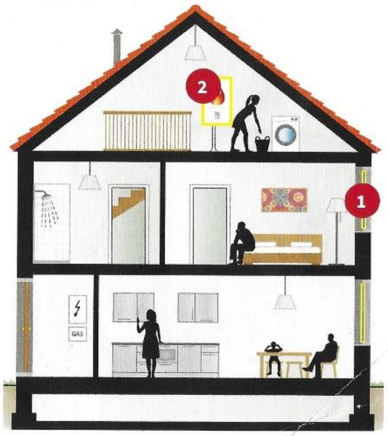
De wonigen uit deze bouwperiode zijn goed geïsoleerd. De minimale eis voor gevel, vloer en dakisolatie was RC = 2,5 m^2K/W. Ook werden de woningen al met dubbelglas opgeleverd.

Het grootste gedeelte van de woningen is voorzien van mechanische ventilatie.

Eigenschappen

- Goed geïsoleerde betonvloer
- Goed geïsoleerde spouwmuur
- Goed geïsoleerd dak
- Mechanische ventilatie
- Centrale verwarming
- Dubbelglas
- Geschat energielabel: C

Hoe kom ik op label B of hoger?



Meer weten? Kijk op woonwijzerwinkel.nl of bel 010 747 01 47

Naar NUL met: Warmtepomp

Een warmtepompsysteem vervangt de traditonele CV ketel. Door gebruik te maken van gratis warmte uit de bodem of lucht kan er met een klein beetje elektriciteit heel efficiënt verwarmd worden. Deze elektriciteit kan dan weer met zonnepanelen worden opgewekt.

Lage temperatuursverwarming is een voorwaarde voor een goede werking.

Uitgangspunten

- Bouwjaar woning na 2005

of:

- Vloerisolatie (Rc ≥ 3,5)
- Gevelisolatie (Rc ≥ 1,8)
- Dakisolatie (Rc ≥ 3,5)
- Glas (U ≤ 1,2)

Efficiënte elektrische verwarming

Meer weten? Kijk op woonwijzerwinkel.nl of bel 010 747 01 47

Appendix 2

GIS model

One of the main objectives of my thesis is to create a spatial model, where the material requirements and their impact are visualized in geographic maps. One requirement was to make a generic spatial model that could run on any computer with ArcGIS in combination with the related spatial data layers. I made the spatial model generic to give follow-up studies and studies that have the same spatial focus, a model that is easily adaptable and implementable in other spatial studies. Whenever the same spatial scope or spatial trade-offs are made in the studies it could be possible to make all sorts of combinations with the spatial data.

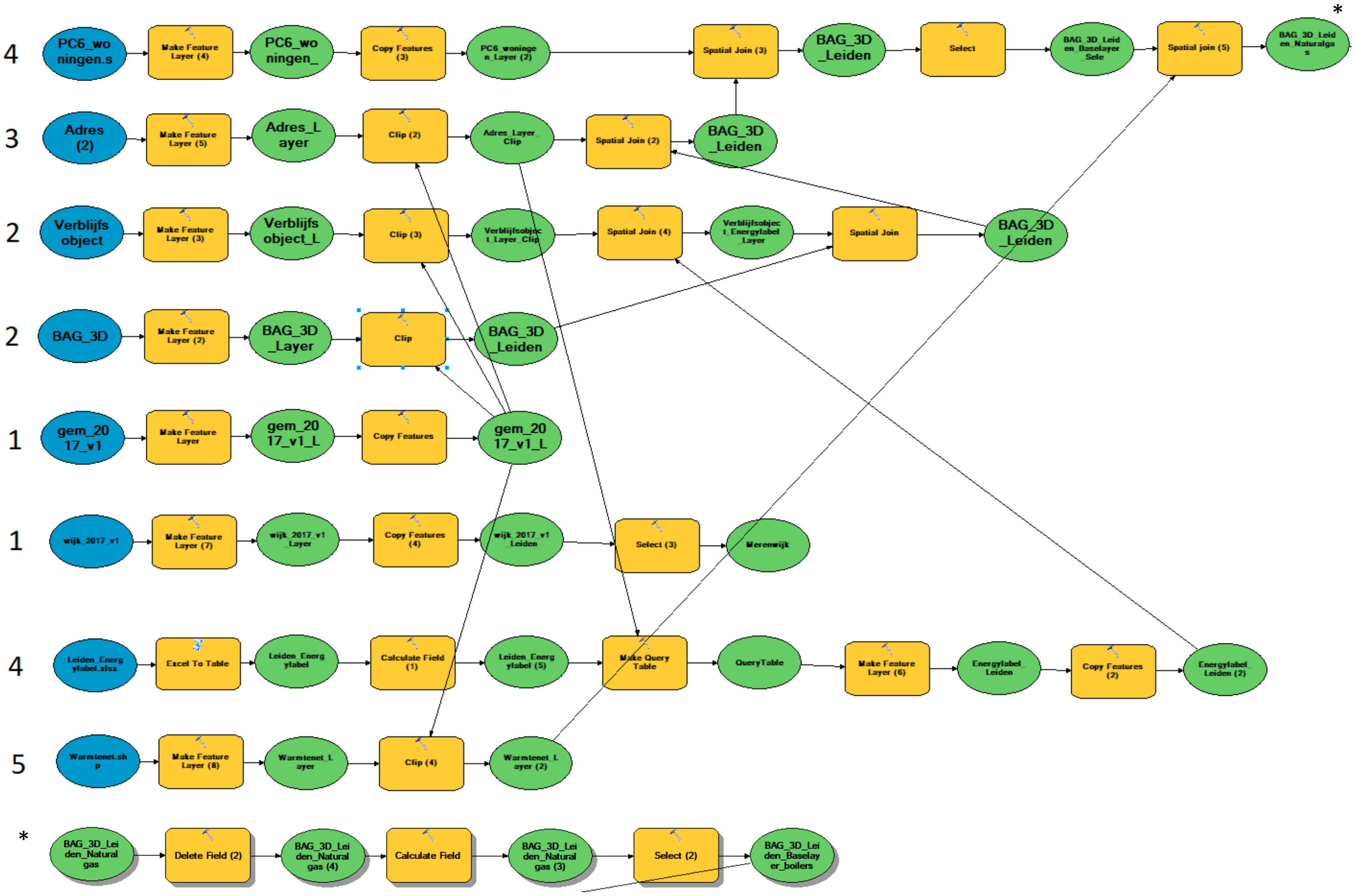


Figure 31 Selection of residential buildings in BAG_3D in model builder

(1) I started with creating the layers that frame the geographical boundaries of my model. I selected the municipality of Leiden out of the gem_2017_v1 layer and selected ‘de Merenwijkdistrict’ out of the wijk_2017_v1 layer. In the beginning part of the model I will use Leiden as clipping feature and later when I get to my results, I will use the Merenwijk.

(2) The BAG_3D layer contains all sorts of buildings and the measurements of the building. The focus of my thesis are residential buildings, I selected the residential buildings by eliminating all the other buildings. To do that I used the Verblijfsobject_v layer, where all purposes of the buildings are mentioned, and selected the residential buildings by creating a feature

layer. With a spatial join of both the Verblijfsobject_v layer and the BAG_3D layer I was able to keep all the buildings with residential purposes inside the BAG_3D layer.

(3) The next step was to calculate the number of dwellings that are in each residential building. For this step I needed the Adres layer. The Adres layer is a vector layer, where every point is an address. To calculate the number of dwellings inside a building I just had to count the amount of points inside a building by using the spatial join function. Joining both layers also means that the data in both layers are joined together. To keep the attribute table structured I kept only the data that was needed for the calculations and the data that gives additional information on the buildings for example street names. This made it easier to check the data with for example Google Maps.

(4) On this point the base layers (BAG_3D) contains the residential buildings with the record of their measurements, construction year and address data. The next step was to add data that provides information on the sustainable performance of the building to be able to estimate the degree of insulation that is present. There are measurements provided by the government to calculate the environmental performance of the building by just looking at the construction year. These measurements give an indication of the degree of insulation that was present in the buildings in the year they were built. However, the improvements over time in the insulation is not considered (Milieu Centraal, n.d.). To try to fill in that gap of knowledge on the improvements that must be made, I added the average household gas consumption on the 6 digits zip code level named PC6_woningen_shp. Also, spatial join was used in this case, to add the data from this layer into the base layer. But natural gas consumption does not always say something about the actual performance of a building. Majcen et al. (2013) found out that the theoretical gas consumption per energy label is far from the practical natural gas consumption of that same energy label. Also, the practical differences between the gas consumption per label was not as significant as was assumed in the theoretical gas consumption of these labels. Therefore, I chose to also implement the energy labels to have a more accurate approach. However, in the energy label layer only 30% of the buildings have a registered energy label. Therefore, for the missing energy labels, improvements in insulation will be estimated by the gas consumption of the buildings. To add the energy labels, I had to import the excel sheet and join the data where the addresses are the same as in the BAG_3D data layer.

(5) At last, in this paper I focus on the material requirement and impact of the transition from natural gas to more renewable. Therefore, people that are already connected to more renewables should not be considered but cannot always be left out because of the data that is not available. The municipality of Leiden have documented their district heat network and can therefore be used to eliminate the connected buildings. This is done by spatial joining the residential buildings (BAG-3D) with the district heating shapefile (warmtenet.shp) and by setting the join distance by 2 meters. This function created a layer where every residential building that is connected to the district heat network was labelled. Now I only had to select all the residential buildings that are not labelled and put that as the base layer. Now I had a BAG_3D layer containing all relevant residential buildings with the data I needed to calculate the material requirements and their environmental impact.

Insulation calculations

The insulation of buildings only happens in the walls that are in contact with the outside air. Neighbouring walls do not need insulation. In ArcGIS the polygon length and area are automatically calculated, in the data named as shape_length and shape_area. The shape_length is the total wall length. That means both the outside facing walls as the neighbouring walls together. As you can see in Figure 32 the neighbouring walls are a significant percentage of the total wall area for intermediate houses. In order to calculate the total wall insulation I found a way to estimate the total wall length that faces the outside air by calculating the total length of all attached buildings together and divide that by the number of buildings in the same block. The steps I did in GIS to calculate this will be explained underneath Figure 32.

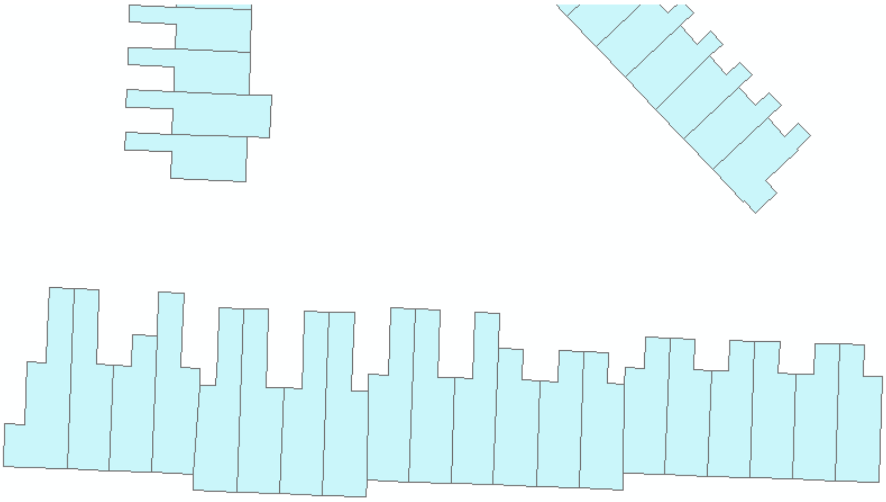


Figure 32 Attached buildings

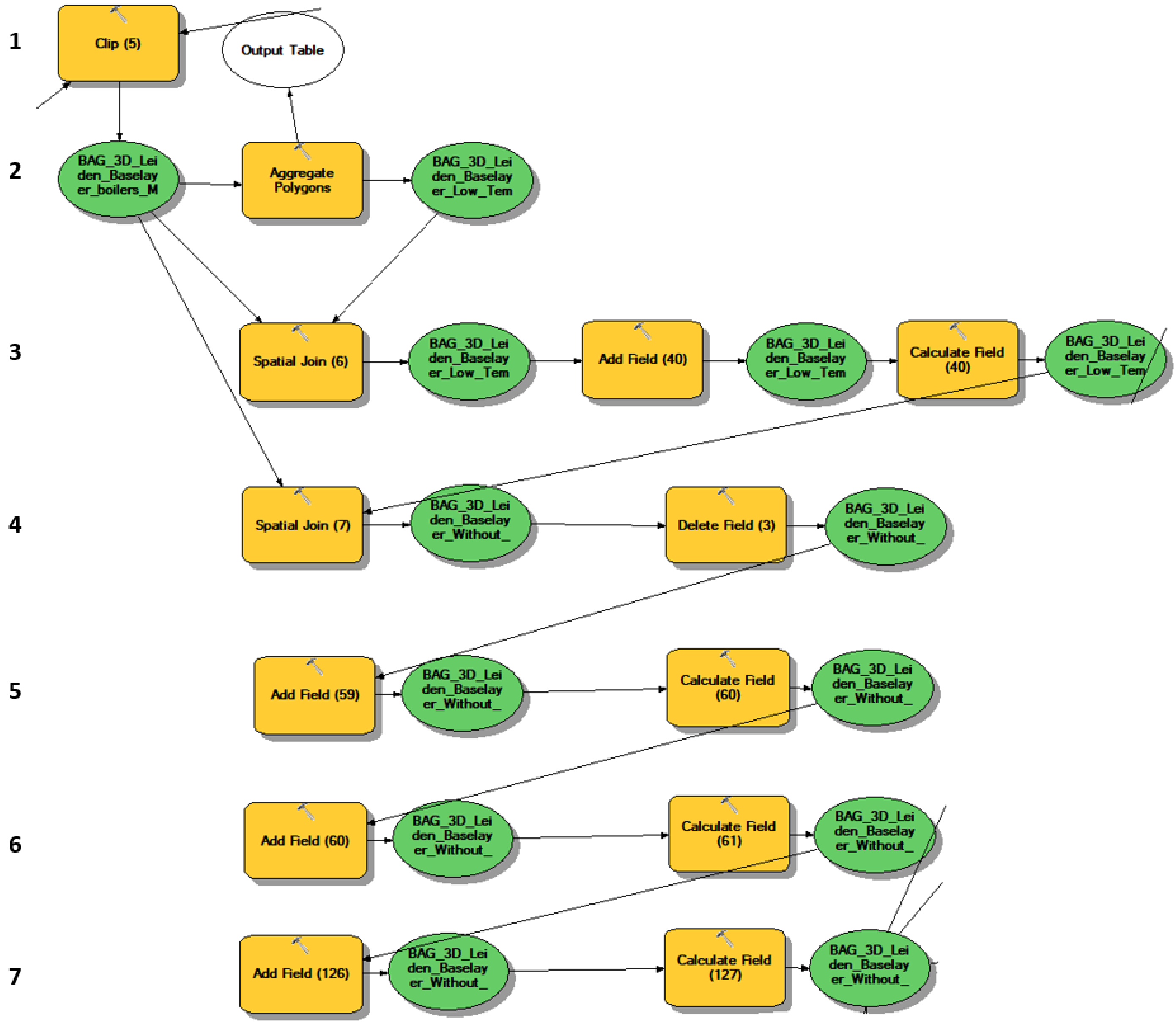


Figure 33 GIS Model calculating average length of outside facing walls

(1) In this step first all previous steps to select the right spatial data and residential buildings is clipped to the Merenwijk.

(2) After the clipping I started with aggregating all connected buildings into one building by using Aggregating Polygon function. The outcome of this function is a layer with all connected polygons as one polygon. For this polygon the shape_length and shape_area is automatically calculated and shown in the attribute table of BAG_3D_Leiden_Baselayer_Low_Temp.

(3) To calculate the average length of each outside facing wall per building in a building block, I needed to know how much buildings were in that block. For this step I spatial joined the original layer, containing the sperate buildings with the aggregated layer, where all the buildings are aggregated together into one building. Now I created a layer containing the shape_length, shape_area and join_count. The join_count I the amount of buildings inside

the block. Now I only had to calculate the average length of the outside facing walls for each building by adding a field: Av_shape_length. In this field the total building block shape_length is divided by the total amount of buildings inside the building block.

(4) Now I have calculated the average length for each building inside the building block. To add this data in the original data layer I spatial joined the original file by the BAG3D_Leiden_Baselayer_Low_Temp1 layer. The end result is a layer containing all the original data with the average shape length added.

There are four areas in a building that need to be known to calculate the amount of insulation needed: The outside facing walls, floor, roof and windows. The floor area is assumed to be equal to the Shape_area, since shapes represents the buildings. In the next steps the roof, wall and window areas are calculated.

(5) In this step the Roof_Area field is added in order to calculate the roof area for each building. The roof area exists of roof and windows. The amount of window per roof area depends on which kind of building it is. So for each type of building the average percentage of windows inside a roof is calculated and extracted from the roof area. The roof area is thus calculated by the type of building and type of roof, flat vs pitched. Pitched roofs were assumed to only exist on buildings with 1 or 2 dwellings and are 1.5 times the size of the Shape_Area. Flat roofs were assumed to exist only on buildings with 3 or more dwellings and is equal to the Shape_Area.

(6) In this step the Wall_Area is added and calculated. The wall area is also reliant on the type of building. For each type the average percentage of windows per wall area is calculated and extracted from the Wall_Area. Also for the wall area it matters if the roof is flat or pitched. For flat roofs the wall area is equal to Av_shape_length times the height of the building. However with a pitched roof it is not the case because the upper floor is a triangle instead of a square. Because the upper floor is a triangle, I assumed that 25% of the squared calculation is wall in the pitched roof scenario and the height of the floor is 3 meters.

(7) The last area is the glass area. For the calculations of this area I added the field Glass_Area and calculated the amount of glass by doing the opposite of what I did for the calculations of the Wall_Area and Roof_Area, and added both together.

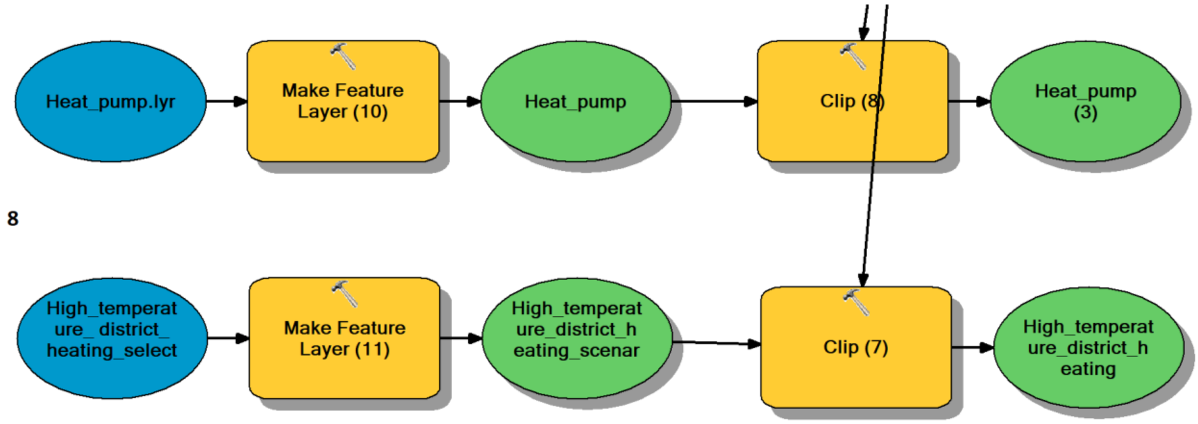


Figure 34 Creating the half heat pump/ half high temperature district heating scenario

(8) In Figure 34 the half/half scenario is created by first selecting both halves by hand within ArcGIS and create a separate layer for both halves These both layers, Heat_pump.lyr and High_temperature_district_heating_selection.lyr are both loaded into the model builder and clipped to the created BAG3D data layer so far.

Now that all characteristics of buildings are loaded into the BAG3D layer I continued with adding all materials and environmental impacts to the attribute table of the BAG3D layer (Figure 35) and adding the appropriate calculations within them (

Figure 36).

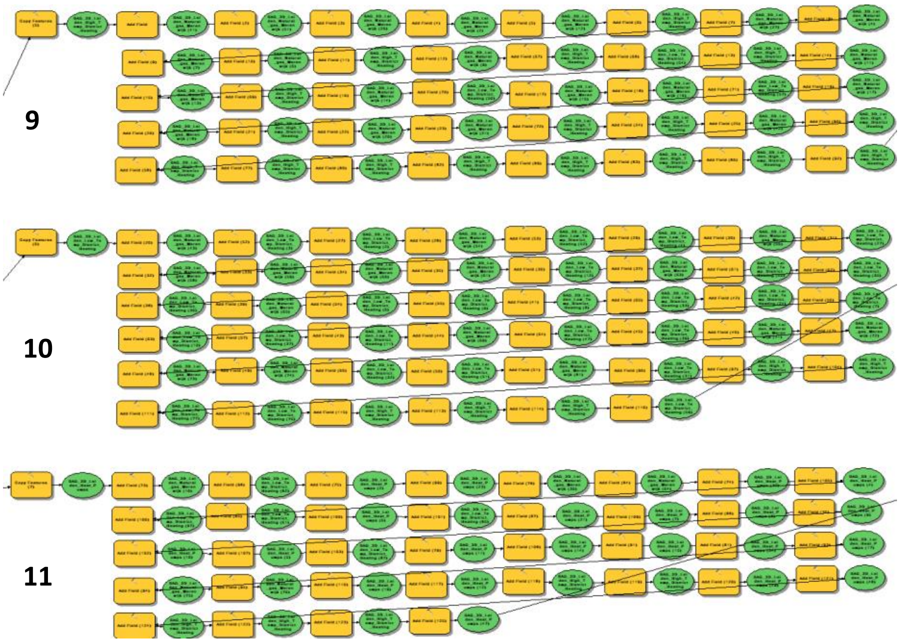


Figure 35 Adding all materials and environmental impacts columns to the attribute table of the BAG3D layer for the three scenarios: 9 = High temperature district heating, 10 = Low temperature district heating and 11 = Heat pumps.

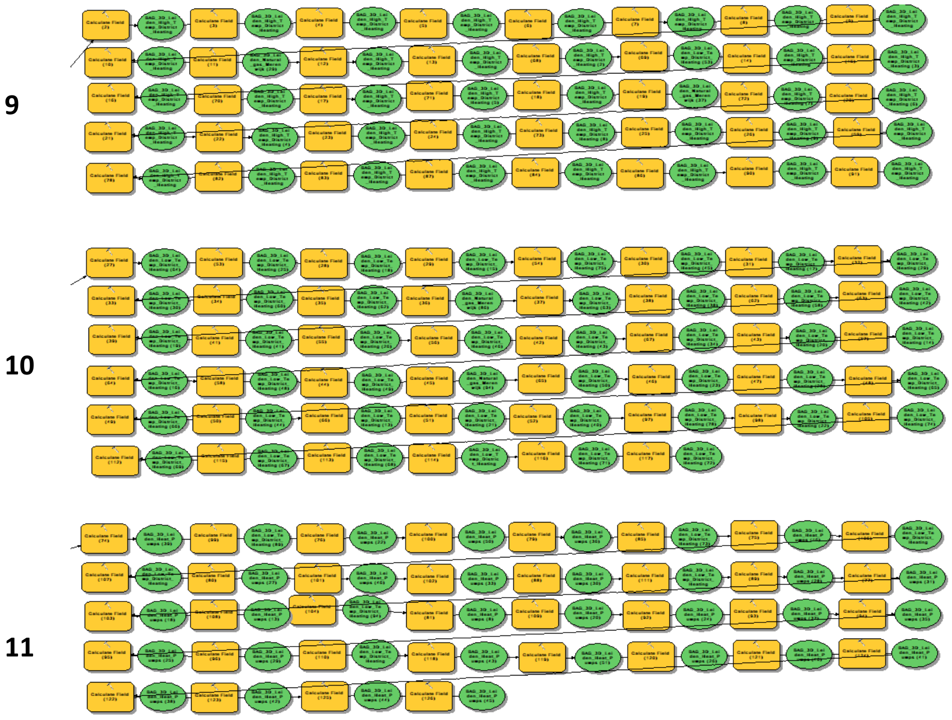
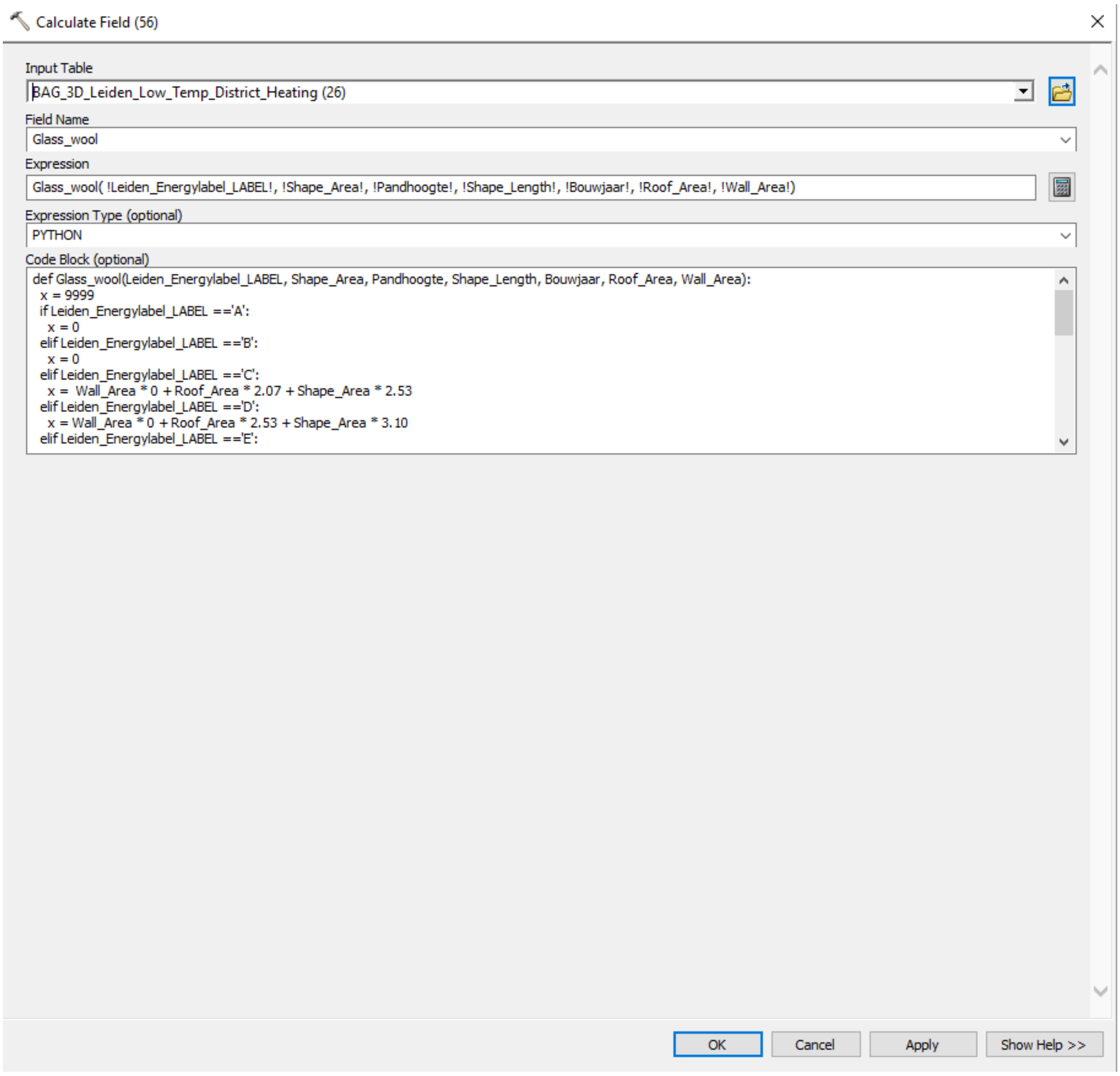


Figure 36 Adding calculations to all material and environmental impact fields for the three scenarios: 9 = High temperature district heating, 10 = Low temperature district heating and 11 = Heat pumps.

An example of such a calculation can be seen in Figure 37, where the amount of glass wool is calculated within the python calculation tool of the model builder. The model inside the model builder of ArcGIS can be found in the supplementary file: 'Merenwijk_Model'.



Input Table: BAG_3D_Leiden_Low_Temp_District_Heating (26)

Field Name: Glass_wool

Expression: Glass_wool(!Leiden_Energylabel_LABEL!, !Shape_Area!, !Pandhoogte!, !Shape_Length!, !Bouwjaar!, !Roof_Area!, !Wall_Area!)

Expression Type (optional): PYTHON

Code Block (optional)

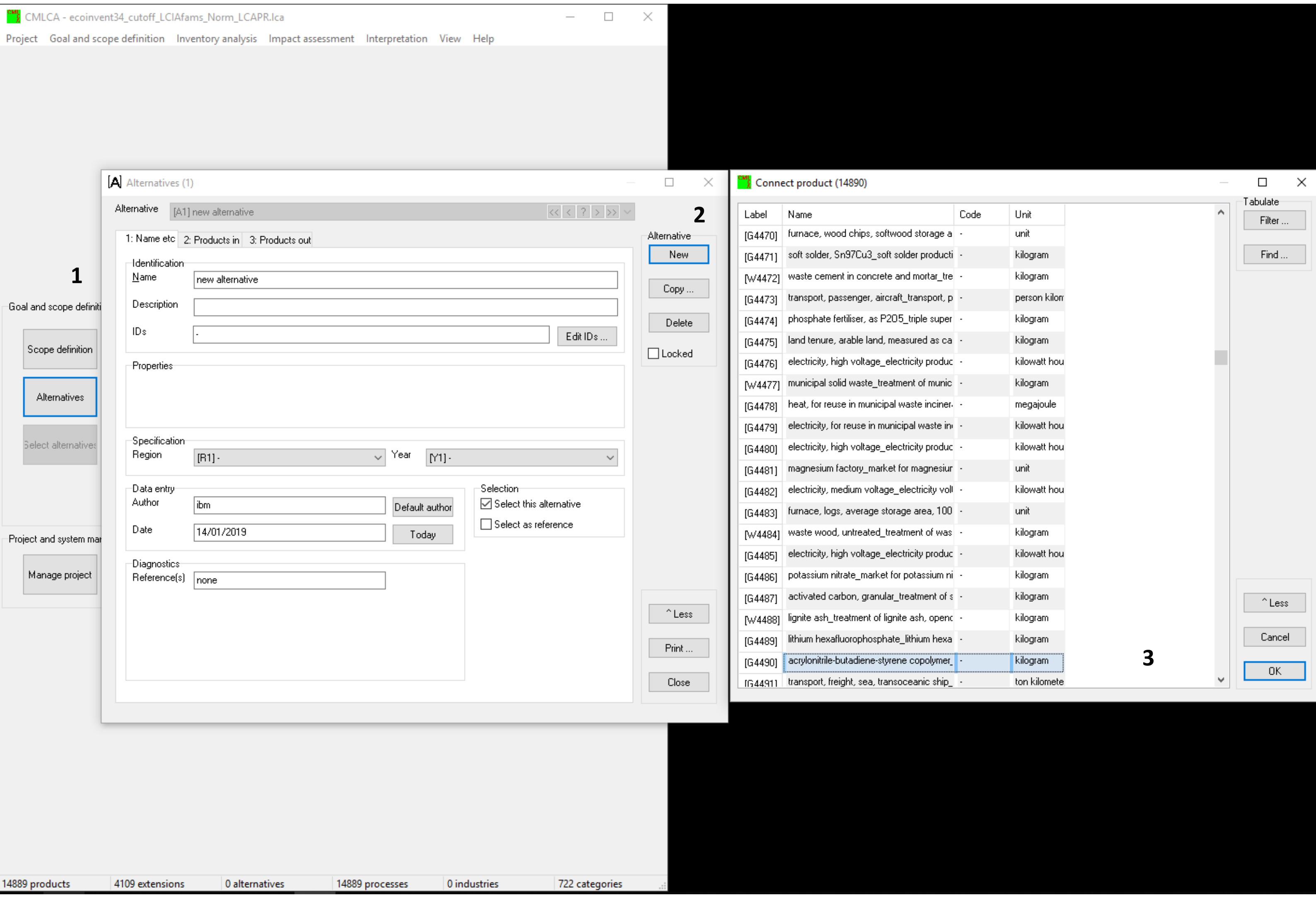
```
def Glass_wool(Leiden_Energylabel_LABEL, Shape_Area, Pandhoogte, Shape_Length, Bouwjaar, Roof_Area, Wall_Area):
 x = 9999
 if Leiden_Energylabel_LABEL =='A':
  x = 0
 elif Leiden_Energylabel_LABEL =='B':
  x = 0
 elif Leiden_Energylabel_LABEL =='C':
  x =  Wall_Area * 0 + Roof_Area * 2.07 + Shape_Area * 2.53
 elif Leiden_Energylabel_LABEL =='D':
  x = Wall_Area * 0 + Roof_Area * 2.53 + Shape_Area * 3.10
 elif Leiden_Energylabel_LABEL =='E':
```

Figure 37 Calculation of glass wool material within the low temperature district heating scenario

Appendix 3

CMLCA

One of the core topics covered in this thesis is the environmental impact of the materials used in each scenario. To calculate this I used the CMLCA 6.1 software tool in order to calculate the environmental impact with the ecoinvent 3.4 database. Ecoinvent is an LCI database that provides process data for thousands of products. I already calculated the material requirements before I started CMLCA, so after I started CMLCA I knew which materials I had to choose. The selection of the required materials can be found in the supplementary excel file: 'Total_materials_scenarios'. Because it is a generic dynamic model I needed the environmental impact per kilogram of material. In order to do that I opened the ecoinvent 3.4 database in CMLCA 6.2. Then I created a new alternative and connected the output of that alternative to one of the required materials from cradle to market. In the example that can be seen in Figure 38 I connected it to the material ABS.



Alternative: [A1] new alternative

Identification
Name: new alternative
Description:
IDs: -

Specification
Region: [R1] -
Year: [Y1] -

Data entry
Author: ibm
Date: 14/01/2019

Selection
☑ Select this alternative
☐ Select as reference

Diagnostics
Reference(s): none

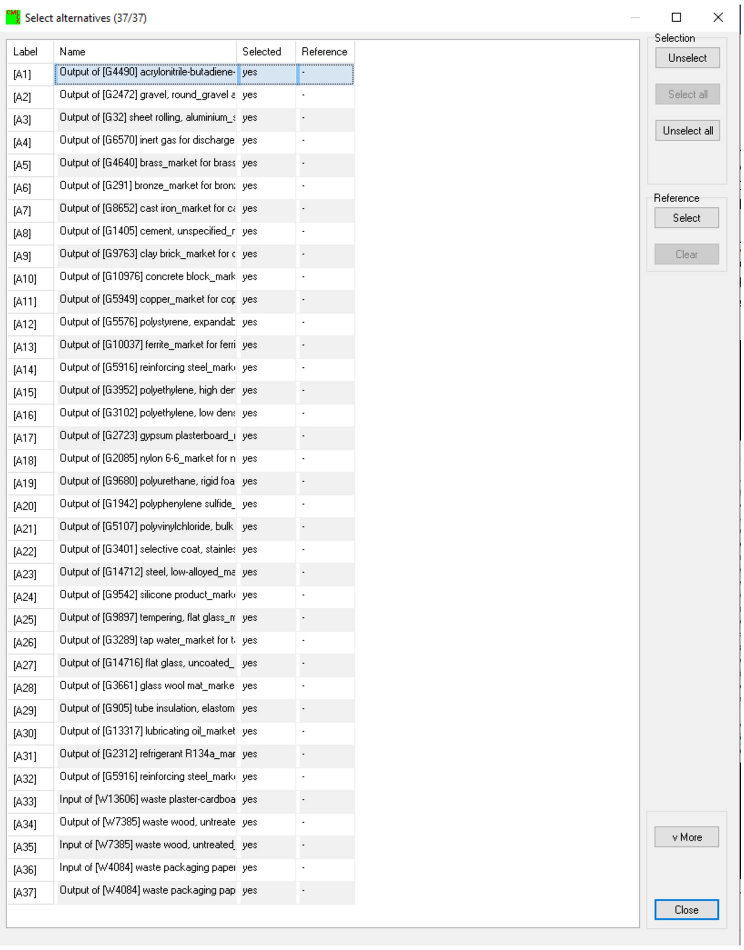
Connect product (14890)

Label	Name	Code	Unit
[G4470]	furnace, wood chips, softwood storage a	-	unit
[G4471]	soft solder, Sn97Cu3_soft solder producti	-	kilogram
[W4472]	waste cement in concrete and mortar_tre	-	kilogram
[G4473]	transport, passenger, aircraft_transport, p	-	person kilom
[G4474]	phosphate fertiliser, as P2O5_triple super	-	kilogram
[G4475]	land tenure, arable land, measured as ca	-	kilogram
[G4476]	electricity, high voltage_electricity produc	-	kilowatt hou
[W4477]	municipal solid waste_treatment of munic	-	kilogram
[G4478]	heat, for reuse in municipal waste inciner	-	megajoule
[G4479]	electricity, for reuse in municipal waste in	-	kilowatt hou
[G4480]	electricity, high voltage_electricity produc	-	kilowatt hou
[G4481]	magnesium factory_market for magnesiur	-	unit
[G4482]	electricity, medium voltage_electricity vol	-	kilowatt hou
[G4483]	furnace, logs, average storage area, 100	-	unit
[W4484]	waste wood, untreated_treatment of was	-	kilogram
[G4485]	electricity, high voltage_electricity produc	-	kilowatt hou
[G4486]	potassium nitrate_market for potassium ni	-	kilogram
[G4487]	activated carbon, granular_treatment of s	-	kilogram
[W4488]	lignite ash_treatment of lignite ash, openc	-	kilogram
[G4489]	lithium hexafluorophosphate_lithium hexa	-	kilogram
[G4490]	acrylonitrile-butadiene-styrene copolymer_	-	kilogram
[G4491]	transport, freight, sea, transoceanic ship_	-	ton kilomete

14889 products | 4109 extensions | 0 alternatives | 14889 processes | 0 industries | 722 categories

Figure 38 Using ecoinvent in CMLCA, creating an alternative (1 & 2) and connect a required material to that alternative (in this case it is the material ABS (3))

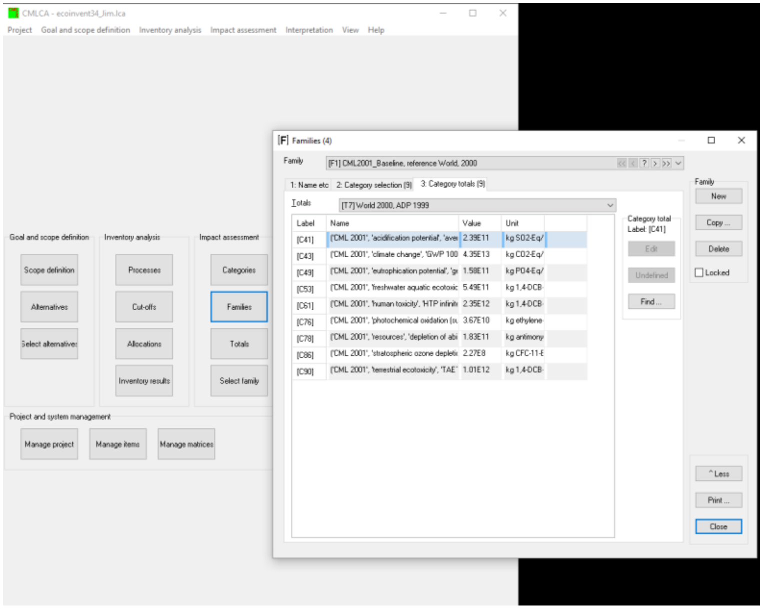
I did the previous step, as shown in Figure 38, 36 more times in order to create a list of all required materials during the heat transition (Figure 39).



Label	Name	Selected	Reference
[A1]	Output of [G4490] acrylonitrile-butadiene-	yes	-
[A2]	Output of [G2472] gravel, round_gravel a	yes	-
[A3]	Output of [G32] sheet rolling, aluminium_s	yes	-
[A4]	Output of [G6570] inert gas for discharge	yes	-
[A5]	Output of [G4640] brass_market for brass	yes	-
[A6]	Output of [G291] bronze_market for bron:	yes	-
[A7]	Output of [G8652] cast iron_market for ca	yes	-
[A8]	Output of [G1405] cement, unspecified_r	yes	-
[A9]	Output of [G9763] clay brick_market for c	yes	-
[A10]	Output of [G10976] concrete block_mark	yes	-
[A11]	Output of [G5949] copper_market for cop	yes	-
[A12]	Output of [G5576] polystyrene, expandab	yes	-
[A13]	Output of [G10037] ferrite_market for ferri	yes	-
[A14]	Output of [G5916] reinforcing steel_mark	yes	-
[A15]	Output of [G3952] polyethylene, high der	yes	-
[A16]	Output of [G3102] polyethylene, low dens	yes	-
[A17]	Output of [G2723] gypsum plasterboard_	yes	-
[A18]	Output of [G2085] nylon 6-6_market for n	yes	-
[A19]	Output of [G9680] polyurethane, rigid foa	yes	-
[A20]	Output of [G1942] polyphenylene sulfide_	yes	-
[A21]	Output of [G5107] polyvinylchloride, bulk	yes	-
[A22]	Output of [G3401] selective coat, stainles	yes	-
[A23]	Output of [G14712] steel, low-alloyed_ma	yes	-
[A24]	Output of [G9542] silicone product_mark	yes	-
[A25]	Output of [G9897] tempering, flat glass_m	yes	-
[A26]	Output of [G3289] tap water_market for t	yes	-
[A27]	Output of [G14716] flat glass, uncoated_	yes	-
[A28]	Output of [G3661] glass wool mat_marke	yes	-
[A29]	Output of [G905] tube insulation, elastom	yes	-
[A30]	Output of [G13317] lubricating oil_market	yes	-
[A31]	Output of [G2312] refrigerant R134a_mar	yes	-
[A32]	Output of [G5916] reinforcing steel_mark	yes	-
[A33]	Input of [W13606] waste plaster-cardboa	yes	-
[A34]	Output of [W7385] waste wood, untreate	yes	-
[A35]	Input of [W7385] waste wood, untreated_	yes	-
[A36]	Input of [W4084] waste packaging paper	yes	-
[A37]	Output of [W4084] waste packaging pap	yes	-

Figure 39 List of required materials as alternatives in order to calculate the environmental impacts

The next thing that had to be done in CMLCA was to select the environmental impacts. For this step I selected in families the CML 2001_Baseline_reference World, 2000 and for the categories totals the World 2000, ADP 1999 in order create an impact category for an average country on global scale (Figure 40).



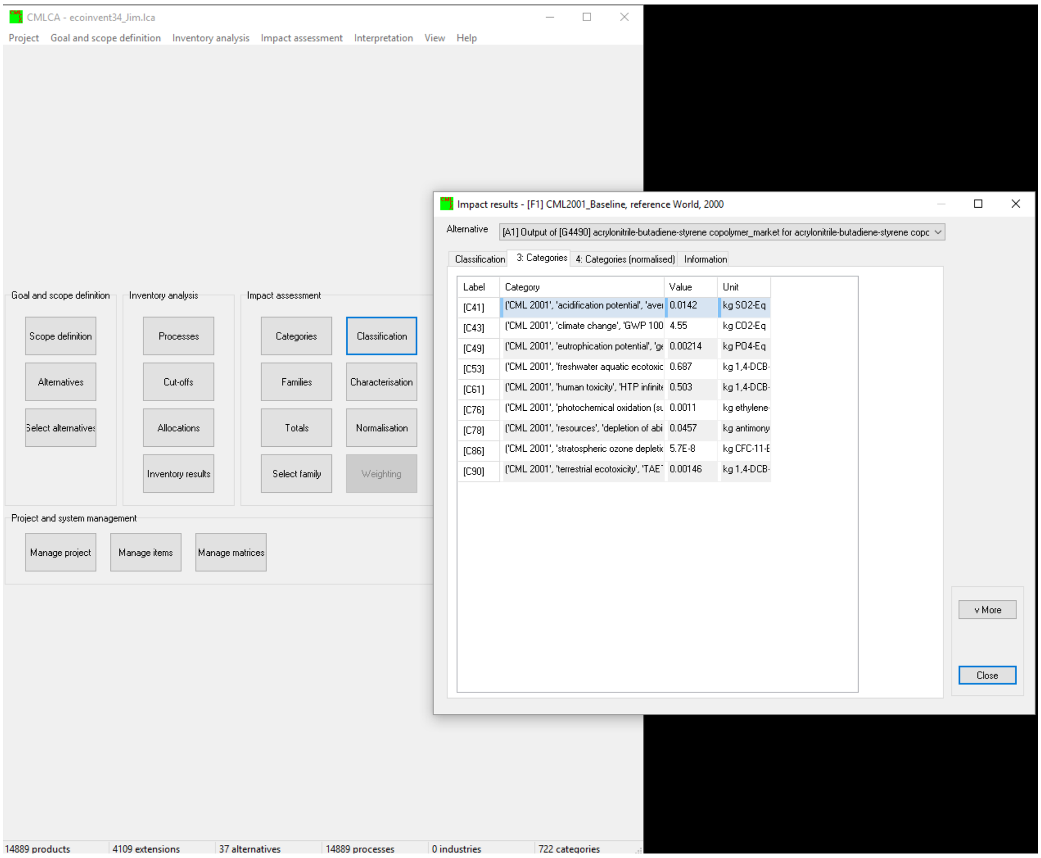
Family: [F1] CML2001_Baseline, reference World, 2000

Totals: [T7] World 2000, ADP 1999

Label	Name	Value	Unit
[C41]	('CML 2001', 'acidification potential', 'ave	2.39E11	kg SO2-Eq/
[C43]	('CML 2001', 'climate change', 'GWP 100	4.35E13	kg CO2-Eq/
[C49]	('CML 2001', 'eutrophication potential', 'g	1.58E11	kg PO4-Eq/
[C53]	('CML 2001', 'freshwater aquatic ecotoxic	5.49E11	kg 1,4-DCB-
[C61]	('CML 2001', 'human toxicity', 'HTP infinit	2.35E12	kg 1,4-DCB-
[C76]	('CML 2001', 'photochemical oxidation (su	3.67E10	kg ethylene-
[C78]	('CML 2001', 'resources', 'depletion of abi	1.83E11	kg antimony
[C86]	('CML 2001', 'stratospheric ozone depleti	2.27E8	kg CFC-11-E
[C90]	('CML 2001', 'terrestrial ecotoxicity', 'TAE'	1.01E12	kg 1,4-DCB-

Figure 40 Selecting the families and categories totals in order select the type of output for the environmental impact calculations

After this step the environmental impact could be calculated for the 9 different impact categories by selecting classification. Now for each alternative all the 9 environmental impact categories are calculated per kilogram of material (Figure 41).



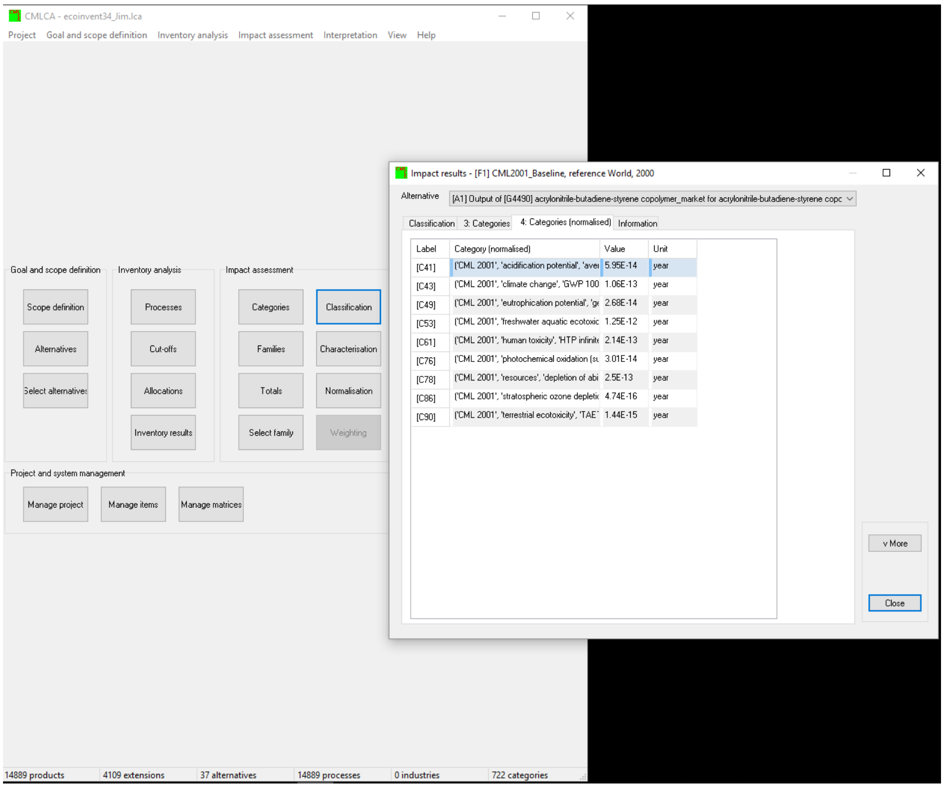
Impact results - [F1] CML2001_Baseline, reference World, 2000

Alternative: [A1] Output of [G4490] acrylonitrile-butadiene-styrene copolymer_market for acrylonitrile-butadiene-styrene copc

Label	Category	Value	Unit
[C41]	('CML 2001', 'acidification potential', 'avei	0.0142	kg SO2-Eq
[C43]	('CML 2001', 'climate change', 'GWP 100	4.55	kg CO2-Eq
[C49]	('CML 2001', 'eutrophication potential', 'ge	0.00214	kg PO4-Eq
[C53]	('CML 2001', 'freshwater aquatic ecotoxic	0.687	kg 1,4-DCB-
[C61]	('CML 2001', 'human toxicity', 'HTP infinite	0.503	kg 1,4-DCB-
[C76]	('CML 2001', 'photochemical oxidation (su	0.0011	kg ethylene-
[C78]	('CML 2001', 'resources', 'depletion of abi	0.0457	kg antimony
[C86]	('CML 2001', 'stratospheric ozone depletic	5.7E-8	kg CFC-11-E
[C90]	('CML 2001', 'terrestrial ecotoxicity', 'TAE	0.00146	kg 1,4-DCB-

Figure 41 Calculating the 9 environmental impact categories for all alternatives per kilogram of material by selecting classification

Now all environmental impact categories for all materials are calculated and put into the supplementary excel file: ‘Total_materials_scenarios’. The last thing to do is to also compare the different environmental impact categories in order to compare their impacts. In order to do that CMLCA also calculates their normalised impact with World 2000 as a reference (Figure 42).



Alternative: [A1] Output of [G4490] acrylonitrile-butadiene-styrene copolymer_market for acrylonitrile-butadiene-styrene copc

Label	Category (normalised)	Value	Unit
[C41]	('CML 2001', 'acidification potential', 'aver	5.95E-14	year
[C43]	('CML 2001', 'climate change', 'GWP 100	1.06E-13	year
[C49]	('CML 2001', 'eutrophication potential', 'ge	2.68E-14	year
[C53]	('CML 2001', 'freshwater aquatic ecotoxic	1.25E-12	year
[C61]	('CML 2001', 'human toxicity', 'HTP infinite	2.14E-13	year
[C76]	('CML 2001', 'photochemical oxidation (su	3.01E-14	year
[C78]	('CML 2001', 'resources', 'depletion of abi	2.5E-13	year
[C86]	('CML 2001', 'stratospheric ozone depletic	4.74E-16	year
[C90]	('CML 2001', 'terrestrial ecotoxicity', 'TAE	1.44E-15	year

Figure 42 Normalisation of the environmental impact categories in order to compare their impacts against each other

Appendix 4

Appendix 5

Interviews

Thomas Engels, Data analyst at Overmorgen

13-03-2018

Kans rijkheid, hoe is dit per warmtetechniek gedefinieerd?

Hoe uitgebreid is dit gedaan en wat waren de speerpunten/guide Lines hiervan? Kans rijkheid bij collectieve warmte (hoge en lage temperatuur oplossingen) en individuele oplossingen. Begonnen bij collectieve warmte alles samenvoegen omdat je met hoog kan beginnen en daarna richting laag kan gaan.

Indicatoren:

- Niet al stadsverwarming (geen gasverbruik)
- Niet al blokverwarming (laag gasverbruik)
- Vrijstaan (woningtypologie)
- Bouwjaar
- Label
- Gasverbruik (openbaar)
- Woningdichtheid wordt in het nieuwe model meegenomen

Op basis van selectiecriteria i.p.v. if else, techniek opsplitsen in individueel en collectief, (geothermie (niet interessant vanwege de bodemdikte), hybride oplossingen en volledig elektrisch).

Het is grotendeels vraag gestuurd, wat wordt er aan energie gevraagd?

Op individuele oplossingen is het niet afgewogen, warmteboiler en hybride cv-ketel bijvoorbeeld. De techniek verandert zo snel dat het moeilijk is om het daarop te baseren, gekeken naar gebouwen. Kijken naar de status en situatie van de gebouwen i.p.v. de warmtetechnieken. Woningtypen is wel beschikbaar maar moet je zelf nog verwerken Blokverwarming is een collectieve ketel. Individuele oplossingen bevatten alleen all electric. Proberen zoveel mogelijk op pandniveau, maar aggregeren terug naar buurtniveau. Kleinschalige lage temperatuur warmtenetten (hoeveel huizen zijn dat?) De schaalgrootte van warmtenetten heeft te maken met de bron en investeringen. Data.overmorgen.nl Storymap.

Bron van de datasets naast kopen?

Beschikbaar stellen als GIS-data van sommige output namens de gemeente. Kosten, uitstoot elementen ingevoegd, uitbreiden van de kaart. Veel data komen van openbare datasets maar gedeeltes worden ook ingekocht van private organisaties

Matthijs de Graaf, manager warmte at Nuon

03-04-2018

Waar komt de warmte van Leiden vandaan?

Eon Leiden valt weg over een paar jaar, 22.546 woningen (niet panden), het liefste praten ze over woning equivalenten. Vanuit Nuon zo'n hoog mogelijke aanvoertemperatuur, laag mogelijk terug voertemperatuur. Hoe warmer de pijp, hoe meer die uitstraalt, maar als je het terug rekent naar hoeveel je doorpompt. De gesprekken over de warmteaanvoer van Leiden, terugkomen naar laagtemperatuur warmte regime. Leveringsovereenkomst tot 2020. Warmtebedrijf Rotterdam (WBR) is vanaf 2020 verantwoordelijk voor de warmtelevering aan Nuon Leiden, is soort van onderdeel van de *warmterotonde*. Hogetemperatuur in de bron, transportnet hoge temperatuur is aanvoertemperatuur 90-120 graden, retourtemperatuur is 67 graden. Retourtemperatuur wordt gebruikt voor een lage temperatuur aansluiting. Onder druk zodat het als water door de pijp stroomt.

Wat zijn de verschillen tussen gas en stadswarmte?

Binnenstad van Leiden aansluiten op stadswarmte, stadswarmte heeft als nadeel dat het onder de grond meer ruimte inneemt dan een gasaansluiting, risicovol en duur voor het centrum. Bestaande bouw proberen ze steeds meer, oude binnensteden zijn heel moeilijk.

- Het bestaande warmtenet is eigenlijk uitgenut, thermische capaciteit limiet is bereikt.

- Het bestaande netwerk kan nog heel veel efficiënter gemaakt worden bij de klanten zelf.

- De leiding uit Rotterdam is niet voorzien op heel veel groei uit Leiden.

Transportnetten wijknetten 70 graden, niet warmer dan 40 graden terugkrijgen. Wordt behandeld water gebruikt, kan problemen opleveren met aluminium radiatoren.

Gaat de *warmterotonde* nog verder uitbreiden t.o.v. het bestaande netwerk?

Is nog niet bepaald, maar zou wel de intentie kunnen zijn. Heineken heeft ook restwarmte

Wat zijn de kosten voor het aansluiten op stadswarmte?

Woningen die aangesloten worden op stadswarmte mogen niet meer betalen dan op aardgas. Nuon is de goedkoopste, met stadswarmte kan je ook variabel ondernemen qua duurzaamheid. Stadswarmte doe je niet voor de rendementen van geld,

Wie gaat de business case maken?

Interactie tussen verschillende bedrijven, het is systematisch waarin het van boven besloten moet worden. Gemeente geeft grond uit en geeft voorwaarden eraan. Nuon zit als partij aan de tafel maar gaat niet over de keuze. Het streven naar lage-temperatuur systemen gaat over de kant van de gebruikers. Het ligt niet aan het transport maar aan de verbruikers kant. Verschil tussen capaciteit centrale en net. Hoe lager de temperatuur, hoe langzamer de temperatuurverandering. Staal in staal is complex en duur maar wel robuust. Die leg je voor 50 jaar in de grond, voor de moeilijk te onderhouden plekken. Levensduur van een normale warmtenetpijp zijn voornamelijk afhankelijk van externe invloeden, anders doe je er ook 50 jaar mee. Storing afhankelijk onderhoud. 80-100 cm grond boven de leiding.

Appendix 6

Model improvements

During the development of the model inside the model builder I encountered some setbacks that must be improved in further studies. The main problems occurred in a later stage, so rebuilding the entire model would have consumed a considerable amount of time.

Entirely generic dynamic model

The results in this thesis are not entirely the results from the GIS model. The gas network calculations are done by hand in Excel. Additionally the calculations on the building and dwelling density are first done in GIS, after which they are modified in Excel, before they are put back into GIS. The modifying step should and could be done however in the model builder of ArcGIS. The missing link why the middle step had to be done in ArcGIS is because the *gasleidingen* layer was missing. After the first results were created I received the *gasleidingen* layer. In order to make it entirely generic and dynamic in the future the calculations for the building and dwelling density should be directly implemented in the material calculations in the last step of the model builder for both the natural gas network as for the district heating network.

Adding removed glass and ventilation systems

I initially focussed on the required materials for the sustainable heat alternatives to calculate that in an automatic way using ArcGIS. However, the material availability from the obsolete natural gas network after implementation of the heat alternatives is also an interesting subject. The materials inside the natural gas network is as already mentioned calculated by hand and did not give any problems. However, also glass windows will be replaced by HR ++ glass for the buildings older than 2005 and for the buildings older than 1983 also the ventilation system is replaced by mechanical ventilation. For the removed glass calculations GIS is needed since it needs the spatial characteristics of each individual building. For the removed ventilation system GIS could be useful as well to select all older buildings than 1983 and calculate their removed materials from the ventilation system. To do this the entire natural gas network calculations should be added to the model and assumptions will have to be made on when buildings will contain single glassed or double glassed windows. However, due to the given time for this thesis this is not implemented into the model, but is certainly possible to add later on I the same way the alternative scenarios are implemented.

Split the model into multiple models

The model builder from ArcGIS is a convenient tool to store and present the steps that are done to come to your results. However, how more steps are added to the model builder, how slower it will react. In the last few steps of the model that I made for this thesis it became eventually too slow to work with. One solution could be to make multiple models, each containing a fraction of the entire model, where in the end an overarching model will refer to the multiple smaller models. Another solution could be to not use the model builder of ArcGIS, but to code the model entirely in python. There are multiple advantages to python compared to the model builder. The two main advantages are that the model is not only limited to the use of the tools of ArcGIS, but can also use tools from other software. The other advantage is that the model will get slower how bigger it gets, when making adjustments and it could run faster than in the model builder. A disadvantage is that for people that are not familiar with python or coding it will be hard to read compared to the model builder of ArcGIS.