Assessing the changes required in the energy infrastructure with regard to the heating transition

An analysis of the materials and associated emissions of constructing the future energy infrastructure

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Abstract

In the Netherlands, almost half of the energy supplied to households is used for space heating. Since natural gas supplies heating fuel to almost 95% of residential buildings Dutch municipalities have to investigate the possibilities of diversifying their heating infrastructure in order to comply with government environmental goals. Possible heating alternatives included in this study are; biogas, district heating and all-electric.

In this thesis, a geospatial model was constructed to analyse the energy demand of the city of Leiden and its energy infrastructure. By combining various governmental datasets in Python and GeoPandas an analysis on the city scale is possible. The main focus of the thesis is material demand for each heating alternative and the associated environmental impact of those materials. The current heating system of natural gas scores lowest on total material demand and embedded carbon. Of the investigated alternatives the district heating scenario has most materials embedded into the infrastructure and also the highest carbon footprint. The all-electric scenario completely replaces heating infrastructure by only utilising electricity for heating. This results in a significant system change with average material consumption. However, the all-electric scenario scores highest for demand in REE's. A combination of heat pumps and biogas resulted in the lowest material consumption of the researched alternatives. This scenario combines the relatively simple conversion to biogas for older houses with the most efficient heating utilising heat pumps for new houses. The major drawback for this scenario would be the sourcing of biomass required for biogas production.

In terms of embedded CO_2 the sustainable heating alternatives proposed in this thesis score higher than the current system. However, the embedded carbon of the building materials would be compensated for in the first year if use-phase emissions are taken into account. The emissions associated with the construction of the supporting energy infrastructure were found to be significantly smaller compared to the use-phase emissions. Together with factors such as heat source availability, investment costs and social acceptance of the heating alternatives municipalities have to decide which heating alternative has its preference.

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1. Introduction

In the Netherlands, more than 40% of the energy consumed in households is used to supply thermal demand (ECN, Energie-Nederland, & Nederland Netbeheer, 2016). In more than 90% of houses thermal demand is being provided by natural gas boilers. Around 84% of the total electrical energy demand is provided by coal and natural gas-powered power plants (R. P. van Leeuwen, de Wit, & Smit, 2017). The combustion of natural gas and coal for electricity and heat generation results in extensive, unwanted, production of greenhouse gasses. Therefore, the Dutch heating system has to fundamentally change in order to reduce its environmental footprint.

In an attempt to reduce the environmental footprint, the Dutch government formulated strategies to drastically reduce the carbon emissions in the coming years. The Dutch government has stated the ambition to be climate neutral by 2050 in order to conform to the Paris agreement signed in 2015. In the Paris agreement, 195 nations agreed to limit the global temperature rise to a maximum of 2 degrees Celsius compared to pre-industrial levels. The climate goals set by the Dutch government require that 20% of the total energy generation is renewable by 2020, the percentage increases to 27% for 2030. Finally, for 2050 the goal is that greenhouse gas emissions are reduced by 80-95% compared to 1990 standards (Rijksoverheid, 2019). As a consequence, the fossil-fuel-dominated Dutch energy sector has to radically change their energy production and consumption methods to enable the Netherlands to reach the climate goals.

Recently the Dutch municipalities became aware of the issues associated with climate change and the need for developing a more sustainable and resilient energy sector. In 2013 more than 40 municipalities in the Netherlands signed the "*Energieakkoord voor duurzame groei*" (Energy Agreement for Sustainable Growth) which would facilitate a reduction in energy consumption and increase the share of green energy in the total energy supply (Sociaal-Economische Raad, 2013). In the agreement, the Dutch municipalities and various stakeholders have established a few climate goals that steer towards the progressive expansion of the renewable energy capacity. The goals which have been established in 2013 and are relevant for the thesis are an average final energy consumption saving of 1.5% each year and an increase in the renewable energy share to 14% in 2020 and 16% in 2023. Although the policy document is seven years old it demonstrates that the Dutch municipalities and their stakeholders are willing to take their responsibilities in the energy transition.

The energy transition in the Netherlands has been ongoing for a couple of years however, the transition to renewable energy sources is moving slowly due to various reasons. One of the key factors which result in dependency on fossil fuels for heating is the lack of alternative renewable heating sources. In the Netherlands, 95% of residential buildings are connected to the natural gas grid and therefore their heating demand is mostly satisfied by the combustion of natural gas in boilers for each individual building (ECN et al., 2016). The remaining 5% of the building stock is connected to a district heating network. This does not necessarily mean that buildings connected to a district heating network are heated in a sustainable manner, as most district heating networks are heated by combined heat and power plants which are mostly powered by fossil fuels (ECN et al., 2016). This is also reflected in the share of renewable energy sources in the energy mix. In 2016, the share of all renewable energy sources was only 6% (CBS, 2016). Upon closer inspection, renewable energy sources involved show that out of this 6% approximately 48% is renewable heat, 43% is renewable electricity, and 8% was renewable energy used in transport.

This thesis will focus on the question of how the Dutch municipalities have to shape their energy infrastructure in order to facilitate the energy transition. The research is focused on the capacity of renewable energy sources which are required to facilitate the heating of residential buildings.

Additionally, an investigation will be conducted on what kind of infrastructure is required between the energy source and the final user. Furthermore, materials required for the construction of the future energy infrastructure will be estimated in order to assess the impact of the Dutch energy transition on global material markets. In the following section, relevant literature on these topics will be discussed.

1.1. Literature review

The adaptation of the city to sustainable heating technologies is a complex matter which is increasingly covered in literature. In this literature review we would like to gain knowledge and insights into the common heating techniques which are proposed for the future. The goal is to gain insight in energy infrastructure composition when a high ratio of renewables are present and how is this different from the current system. The observations with regard to afore mentioned problems are discussed in the first part of the literature review. Furthermore, the characteristics of the proposed heating techniques such as component material content, material intensity per unit or kilometre (in case of cables and pipes), lifespan and energy efficiency. In addition to covering the heating techniques electricity production and transportation techniques are taken into account to gain a complete overview of the energy system. Specific information about the heating and electricity techniques involved in this research are described in the second part of the chapter.

The energy transition can be examined from various angles, but Bridge, Bouzarovski, Bradshaw, & Eyre (2013), have described the energy transition as a “geographical process”. Bridge and colleagues state that the energy transition is foremost a geographical problem as we have to deal with a reconfiguration of patterns and scales of economy. Reconfiguration of patterns is demonstrated by the need for reconfiguration of our energy infrastructure to be able to cope with increasingly more local energy production and intermittency of renewable sources. This notion is also underlined by Balta-Ozkan, Watson, & Mocca (2015) as they noted that clustering of low carbon energy technologies would cause congestion in existing power networks. The latter aspect, scales of economy, also determine decision making within the energy transition as larger-scale energy systems requires different policy decisions to be cost-effective compared to small localised systems. The last point which Bridge and colleagues mention is that development of low-carbon energy systems is more likely to happen in regions which/that lack natural energy resources. The Netherlands is in such a position as the natural gas field in Groningen have to reduce their production in order to prevent earthquakes. On the other hand, the potential for renewable energy generation in the Netherlands is rather large (Jacobson et al., 2017).

Resource scarcity, which was mentioned in the previous paragraph, can be a determining factor for the development of low-carbon energy systems and can also be interpreted in light of the energy system construction. The environmental impact which can be associated with construction materials and energy production techniques is being studied extensively in recent years (de Koning et al., 2018; Kleijn, van der Voet, Kramer, van Oers, & van der Giesen, 2011). Kleijn and colleagues (2011) describe that low-carbon energy systems are more metal-intensive when compared to fossil fuel-based energy systems. The increased metal intensity might prove an obstacle for the energy transition as some vital materials for low-carbon energy systems might not be sufficiently available. In their recently published work, De Koning and colleagues (2018) once again confirm that the energy transition will cause a significant rise in metal demand. But while the increase is steep, they do not label the increase in demand as an “extreme” increase. Both of these papers stress that it is important to be aware of the expected increase in metal demand and act accordingly to prevent metal supply from being a bottleneck for the energy transition.

Similarly, the material requirements of low-carbon energy systems can also be viewed from the supply-side of materials. Potential disruptions in the supply of materials could endanger the transition to low-carbon energy systems (Roelich et al., 2014). Disruptions in the supply of materials and exposure of the system to those disruptions are defined as material criticality. This concept is used to evaluate the relative risk for disruptions of the energy transition and a potential future lock-in to a technique which requires highly critical materials. A historical example of such a problem is the neodymium crisis in 2010 as described by Sprecher et al. (2015). The neodymium crisis resulted in the neodymium magnet supply chain being disrupted and users suddenly having to pay high prices or investigate substitutionary metals. By quantifying the material requirements of the energy transition such problems could be prevented.

In the 21st century, the environmental challenges force society to change from fossil fuel energy sources to renewable energy sources. Traditionally, the power grid in the Netherlands was designed to supply electricity from a limited number of central generators to widespread local grids. The central generators were large fossil fuel-driven generators which produce extensive amounts of energy on demand and had a lifetime of roughly 40 years (Connolly, Lund, & Mathiesen, 2016). On the other hand, low-carbon energy sources are characterised by fluctuating production, localised production and increase bi-directional electricity loads (Naber, Raven, Kouw, & Dassen, 2017). These new characteristics demand a reconfiguration of energy network design. Several authors (CE Delft & KEMA, 2012; Naber et al., 2017) are therefore advocating upgrading the current grid to deal with new challenges in the electricity network. Upgrading energy infrastructure will lead to a few challenges which will be addressed in the following paragraphs.

Intermittency of energy production is inherent to renewable energy sources such as solar and wind. Energy production fluctuates in time due to weather conditions and time of day. For example, solar photovoltaic panels (PV) and solar water heaters have their peak production during daytime hours, while wind energy production might fluctuate more during the whole day and even during several days. On average, on the Northern hemisphere, solar and wind energy are approximately complementary to each other as solar production peaks during clear days, while on cloudy days there is usually more wind (R. P. van Leeuwen et al., 2017). However, the balance between solar and wind power is far from perfect and therefore high shares of solar and wind energy in the overall energy mix can lead to imbalances in the energy grid. In order to deal with intermittency issues of renewable sources, it is deemed essential that the electricity grid is connected on a large, possibly European, scale in order to balance the intermittency of renewable energy sources when their contribution to energy mix increases substantially.

That being said other authors argue that energy infrastructure built at a local scale has advantages over a centralized system with regards to resilience, increased potential to integrate renewables and reduced transmission losses (Busch, Roelich, Bale, & Knoeri, 2017). Most apparent advantages can be seen in district heating networks. These networks have the potential to significantly reduce the emissions of a heating system and increase heating efficiencies. Heat can be sourced from nearby solar heater panels, geothermal sources or residual heat from industry. However, due to district heating networks transporting actual hot water, they need to be carefully designed to reduce energy losses (Werner, 2017). Similar principles are valid for local electricity generation as matching local generation and consumption of electricity will also benefit the whole electricity network in terms of stability. Additionally, a local grid could be designed in such a way that supply and demand for energy are better matched compared to energy systems on a large scale. Balancing supply and demand of energy, but renewable energy in particular, can be improved by storage of energy (Connolly et al., 2016; Mathiesen et al., 2015). Applications for energy storage such as batteries, kinetic storage in water reservoirs or heat storage underground come to mind. However, due to the mechanical complexity of these applications they are left out of scope in this thesis.

According to Connolly et al. (2014) integrating fluctuating low-carbon energy sources is done more easily if the heating, electricity and transport sectors are connected. They assume that in a merged system combined heat and power (CHP) plants, district heating and heat pumps are used to produce energy for the built environment. Their research demonstrates that merging of the heating and electricity sector can facilitate a renewable energy share of up to 40% without reducing fuel efficiencies of the system. In order to increase the share of fluctuating energy sources further, the transport sector is added to the combined energy system. The transport sector is vital because in the future electric vehicles can significantly increase the energy storage capacity of the grid. These propositions ensure that the demand-side of the energy system can be adjusted to the supply-side more easily. Providing a flexible energy system where supply and demand for energy can be matched is vital to facilitate 100% renewable energy generation and replace fossil fuels. This concept is called the Smart Energy System concept.

The combined energy sector which is mentioned in the previous paragraph forms the basis for studies which research the feasibility and impact of 100% renewable energy systems for the future. Connolly et al. (2016) calculated the impact of a fully renewable energy system for the EU. They found that the Smart Energy System will require higher investments (12%) than a business-as-usual scenario, but this is counteracted by increased local job creation in the EU and 100% renewable energy usage. In addition to changing the supply-side of the energy system, Jacobson et al. (2017) found that transitioning to 100% renewable energy also reduces end-use energy demand by 42.5% compared to business-as-usual in 2050. Reduction in end-use energy demand is caused by higher efficiencies of renewable space heating systems, electric vehicles and reduction in energy required for mining fossil fuels.

The renewable energy system of the future requires different energy sources compared to mostly fossil fuel-based energy sources which are currently used. The main heating techniques which are compared are heating by natural gas, biogas, low-temperature district heating, high-temperature district heating and utilising heat pumps (also called all-electric). A more detailed section on each of the energy technologies and their technical characteristics and material intensities will be provided in next sections.

In the following sections of the literature review the heating and electricity technologies which are taken into account will be discussed. This section will provide the general characteristics of each technology and the current status of each technology in the Netherlands. Relevant space heating technologies will be discussed first and thereafter the electricity technologies. In the corresponding subchapter transportation technologies for electricity and heat will also be discussed. Information provided in this section provides the basis for the material database which is used in the model. The complete description of all material data which is utilised in the model can be found in Appendix C.

1.1.1. Technology review – Natural gas

Space heating by natural gas has been utilised in the Netherlands since the 1960s. During that period the Netherlands faced its first heating transition which resulted in replacing coal with natural gas for space heating. In the twentieth century, another heating transition is on the cards and natural gas heating has to be replaced by more sustainable alternatives. The natural gas distribution network in the Netherlands is very extensive as around 95% of Dutch houses are connected to the natural gas grid. The total length of the natural gas distribution network is estimated to be around 136632 km (Netbeheer Nederland, n.d.). The main distribution network in the Netherlands is maintained by GasTransport Services and the regional networks are maintained by nine different network operators.

Most of the natural gas pipes are made from of steel or plastics, only 2.5% of the remaining natural gas pipes are made from cast-iron. Especially these cast-iron pipes are due for replacement as they pose a large risk for gas leaks due to oxidation and vibrations in the soil. Network operators are actively monitoring the remaining cast-iron pipes and replacing them when the risk of incidents surpasses a certain threshold only known by the network operator themselves (Netbeheer Nederland, 2019). The average pressure in the main transport lines is 67 bar, but once the natural gas is distributed among regional networks the pressure is reduced to 30 millibars and the typical gas scent is added for safety reasons (Netbeheer Nederland, n.d.). On average natural gas pipelines have a lifetime of 30 to 40 years (Stedin, 2016). Replacing natural gas infrastructure is a costly endeavour because a pipeline has to be dug out which has considerable costs due to labour and obstruction of public or private space. Therefore, replacement of natural gas infrastructure is often combined with maintenance on other pipelines in the underground. Careful planning of maintenance duties is required in order to lower costs and limit disturbance to the general public.

The major components of the local natural gas infrastructure are pipelines and pumping stations. In **Error! Reference source not found.** the major components of the natural gas infrastructure are described. In appendix C the complete material inventory data can be found. The material data was based on a database provided by Liander on the gas infrastructure present in the city of Leiden and material inventories found in the literature (Oliver-Solà, Gabarrell, & Rieradevall, 2009a). It was assumed for modelling purposes that the high-pressure natural gas pipes were made out of steel. Low-pressure pipes were made out of PVC. In this model, it was assumed that each household had a HR boiler present in their home for space heating.

*Table 1 Main components of the natural gas system. *mostly limited by well lifespan. Source* Oliver-Solà et al., 2009.

Component	**Main materials**	**Estimated lifespan**	**Comment**
Natural gas drilling and production	Concrete & steel	15-50* years	Mainly based on Ecoinvent 3.4
HR boiler	Steel, copper & PVC	15-20 years	Efficiency of 90%
High pressure transport pipes	Steel	15-50 years	HTL 400mm and local 150 mm pipes
Low pressure delivery pipes	PVC	15-50 years	200, 140 and 32 mm pipes

1.1.2. Technology overview – Renewable gas

Renewable gas, or biomethane, is similar to natural gas which is currently used for space heating. Biogas is upgraded from regular biomethane in order to achieve the same quality as fossil natural gas. In order to achieve the same quality as natural gas the methane content is upgraded from around 60-65% to at least 88% (RVO, n.d.). Therefore it is possible to use the existing gas grid to distribute the biogas (Kiwa & Netbeheer Nederland, 2018). Combustion of biogas can be done in boilers which are already installed in most houses and therefore the household boilers do not have to be upgraded.

In the Netherlands, it is not possible to produce the total required volume of biogas to completely substitute fossil natural gas. Additionally, the biomass resources of Europe as a whole are too small compared to the energy which is required by European countries (Connolly et al., 2014). Increasing renewable gas production will most likely be achieved through increased fermentation of "wet waste flows" such as manure, sewage sludge and seaweed (De Gemeynt, ECN, Groen Gas Nederland, & RVO, 2014). It is expected that in 2020 around 1.2 billion cubic metres of renewable gas can be acquired in the Netherlands, which is equal to 0.75 billion cubic metres of natural gas equivalent, or 15-20 PJ. In 2030 these numbers rise to 3.7 billion cubic metres of renewable gas and 2.2 billion cubic metres of natural gas equivalent, or 75 PJ (De Gemeynt et al., 2014). Taking into account the efficiency gains in the energy demand De Gemeynt et al. estimate that biogas could provide up to 15% of the energy supply in 2030.

Renewable gas is suitable in local projects such as in Meppel, the Netherlands(Richard P. van Leeuwen, Fink, de Wit, & Smit, 2015). In this energy system biogas is combusted in a combined heat and power plant (CHP) and high-temperature hot water storage. Essentially, biogas drives the CHP to supply a high-temperature district heating network and provide power to houses which are not connected to the district heating network (Richard P. van Leeuwen et al., 2015). Hence there are two different pathways in which renewable gas could be utilised in the future, but the quest for acquiring enough biomass for biogas production remains.

Therefore, this option does not seem viable to fully replace natural gas as the main heat carrier in the future. Renewable gas might be suitable in Dutch inner cities which contain a majority of monumental houses. These monumental houses cannot be renovated sufficiently to utilize lower temperature heating technologies. Even though the viability of heating by renewable gas can be questioned the system is analysed in this thesis. The major components are similar to the natural gas system as most infrastructure can be reused. In **Error! Reference source not found.** the major components of the renewable gas infrastructure are described, the more detailed overview can be found in appendix C.

Table 2 Main components of the renewable gas system. Sources Oliver-Solà et al., 2009a; Vu, Vu, Jensen, Sommer, & Bruun, 2015

Component	**Main materials**	**Estimated lifespan**	**Comment**
Renewable gas production plant	Steel & chromium	15-20 years	Mainly based on Ecoinvent 3.4
HR boiler	Steel, copper & PVC	15-20 years	Efficiency of 90%
High pressure transport pipes	Steel	15-50 years	HTL 400mm and local 150 mm pipes
Low pressure delivery pipes	PVC	15-50 years	200, 140 and 32 mm pipes

1.1.3. Technology overview – District heating

District heating is defined as “Distribution of thermal energy in the form of steam, hot water or chilled liquids from a central source of production through a network to multiple buildings or sites, for the use of process heating and cooling.” by the European Commission in 2016. Generally, a district heating system in the Netherlands is a network of pipelines filled with a fluid which distributes heat. Usually, pressurized water is used to transport heat as this is abundantly available. In the definition by the European Commission steam is considered to be a heat distribution medium, but in Western Europe, steam is not used when supplying heat to households. In general, two types of district heating systems are distinguished namely the high-temperature and the low-temperature variants. In principle, both systems are identical in their operating mechanics but only the temperature of the heat transport fluid is different. Low-temperature district heating networks operate below 55°C and high-temperature district heating networks operate between 55°C and 90°C. Some general information on district heating networks in the Netherlands will be provided first before specific technical and material information will be presented for each of the district heating types.

In 2015 the number of houses which were heated through district heating was estimated to be around 410000. In total, more than 150 TJ of heat was provided through major district heating networks in 2015 (CBS & ECN, 2017). However, heat which is supplied to these networks mainly originated from coal and natural gas power plants (78%). Only 15% of the total district heating was supplied by renewable sources in 2015. The main renewable source was provided by combustion of the biogenic fraction of municipal solid waste (CBS & ECN, 2017). On average the energy losses of district heating systems present in the Netherlands were estimated to be 25% (CBS & ECN, 2017). CE Delft reported that more advanced heating networks only have 15% losses during the transport phase. A lot of variation was found between losses of several district heating networks, but in general, losses were higher in networks consisting of a lot of small consumers compared to networks which provide heat to several large consumers. Therefore, in this thesis the average value of 20% losses during heat transport will be taken into account.

For modelling purposes in this thesis, the district heating system is simplified. District heating systems can work with constant or variable water flow and temperatures. The water flow and temperature of the system are able to adapt to the heating demand and outside temperature to ensure that the heating demand of the houses is met. In this model, a district heating system with constant water flow and constant temperatures is chosen. This means that the system operates at maximum heating load, maximum temperature and maximum flow rate (Pirouti, Bagdanavicius, Ekanayake, Wu, & Jenkins, 2013).

Low-temperature district heating networks only constitute a small fraction of the total district heating networks. This is mainly due to the low-temperature variant mainly being suited to newly-built houses. New housing, which has to conform to strict building legislation, is properly isolated to deal with lower temperature heating. The strong link between low-temperature heating networks and newly-built houses means that an increase in the share of low-temperature district heating can be expected in the future. This is also due to stricter environmental policy demands a new development project to build houses which lack natural gas connections and require appropriate insulation for reaching energy label A or better (RVO, 2019).

1.1.3.1. Technology overview – Low-temperature district heating

The lower temperature of the water in the system limits losses during transport.
On the other hand, the lower feed-in temperature of the network would mean that houses need to be adapted to effectively use energy for space heating. This would require increased insulation, ventilation and alternative radiators (van der Kooij, 2019). These alterations in the building might require extensive investments in existing housing to be able to adapt to low-temperature space heating. Typically houses with energy label D or better can be adapted to using low-temperature district heating (CE Delft, 2019a). However, buildings with energy labels D to B would require a more powerful heat pump to produce enough heating for comfortable living conditions. Houses with an energy label A or A+ demand a space heating temperature of 40°C and can, therefore, be connected to low-temperature district heating networks without additional heat pumps. As the temperature of the heating network is rather low and no boiler is present in the houses a heat exchanger needs to be present to heat water for domestic hot water use. Dutch law requires hot tap water to be at least 55°C (CE Delft, 2019a). It would only require a 3 kW heat pump for heating of domestic hot water from 30°C to the legal minimum.

Heat sources which usually used to provide energy to low-temperature district heating systems are geothermal heat sources, CHP plants, sewer heat, solar thermal heat and waste heat from cooling data centres or supermarkets. As long as the source temperature is between 30 and 65°C (CE Delft, 2019a). The environmental performance of low-temperature district heating networks is therefore mainly determined by the sustainability of the heat source.

1.1.3.2. Technology overview – High-temperature district heating

The typical temperature of this variant has a minimum of 70°C and returns from the house to the system at around 40°C. These temperatures are similar to temperatures produced by natural gas boilers. This means that fewer adaptations are required in houses which are connected to the high-temperature district heating system. The temperature of the network enables direct use for hot tap water and no additional boiler would be required. Suitable heat sources for a high-temperature system are residual heat of industry, waste incineration facilities or power plants.

Several high-temperature district heating networks are constructed in the Netherlands. In Leiden, a high-temperature district heating system is operational in a few neighbourhoods. Residual heat produced by the EON power plant (natural gas-powered) is utilized to heat houses and businesses in Stevenshof and small parts of Roomburg and Merenwijk. However, the EON power plant which provides all of the heat for the system is closing in 2024. Several other projects are investigating the possibility of connecting the district heating network of Leiden to the system in Rotterdam or The Hague. Additionally, heat could be sourced through the HAL project which utilises geothermal heat. Lastly, Leiden and The Hague are collaborating in their endeavour for finding alternatives to provide heating to existing district heating networks in the respective cities.

The project which connects the district heating system of Rotterdam to Leiden and The Hague is called *"de Warmterontonde"* (Heat roundabout). The project would utilise industrial residual heat to provide heat to several of the cities around Rotterdam. The goal of the project is to provide between 40 and 60 PJ of sustainable heat to the province of South Holland. This means that between 50 and 75% of the expected heating demand of the region in 2050 could be supplied by residual and geothermal heat. Main advantages of this system are that the residual heat of the industry in Rotterdam is not wasted and that high-temperature district heating can replace space heating by natural gas (Projectteam Cluster West, 2015). In order to build a system which does not rely on natural gas the remainder of the heating demand would have to be sufficed by other renewable heating sources.

However, there are concerns with regards to the proposed system. Construction of this project would create a lock-in by making several cities dependent on fossil fuel-powered industry in the Rotterdam harbour. It creates a monopoly position for the heating suppliers, which could lead to high prices for the supplied heat.

In comparison to a low-temperature district heating network, no major adaptations to houses are required if previously the heat was supplied by natural gas boilers. The district heating source can directly be connected to the central heating system in a home as the water has a similar temperature to boiler heated water. The higher temperature of the delivered heat means that regular radiators and space heating applications can still be utilised. The only adaptations which have to be made are cooking without natural gas. As all of the heat is delivered by the district heating network the natural gas connection can be removed. The environmental performance enhancement will mainly be based on the environmental performance of the heating source. A high-temperature system allows for the heating source to be changed in the future if required. The only requirement for changing the heat source would be that the operating temperature remains in a similar range as before. Although the natural gas usage of a home is removed the cost of the energy remains largely the same (CE Delft, 2019b).

The major components of a district heating system are pipelines for water transport, surface boxes and pumping stations. In **Error! Reference source not found.** the major components of the district heating system are presented. The detailed overview of materials associated with each component can be found in appendix C.

Table 3 Main components of district heating systems. Sources Oliver-Solà, Gabarrell, & Rieradevall, 2009b

Component	**Main materials**	**Estimated lifespan**	**Comment**
CHP plant	Concrete, steel & ceramic brick	15-20 years	As a replacement for generic industry. Mainly based on Ecoinvent 3.4
Heat exchanger	PVC, Steel & copper	15-20 years	
High pressure transport pipes	PE, Steel	15-30 years	Warmterontonde pipe 500 mm
Low pressure delivery pipes	PE, Steel	15-30 years	300, 150 and 50 mm pipes

1.1.4. Technology overview – All-electric

Heating houses through utilising heat pumps is called the all-electric scenario in many policy documents. It is called all-electric as the heat pump, which is used at the residential level, is powered by electricity and the house would not use any other source of heat except the heat pump. In general, three different types of heat pumps are used: geothermal, air and water source heat pumps. In the Netherlands, geothermal and air heat pumps are considered viable options for residential heating. One requirement for houses to utilise an all-electric heat pump is that the house is properly insulated, which mostly applies to houses in the Netherlands built after 1992. With regard to this thesis, the materials required for the insulation are not taken into account.

Aspects which are taken into account in this thesis are the consequence of large areas converting to all-electric scenario. When houses are converting to the all-electric scenario it would mean that the power infrastructure has to be improved. Next to the regular electricity consumption of a household, the entire heating demand has to be supplied by electricity. In most cases, this would mean that the electricity demand of a household increases significantly. The first step which prepares a home for utilisation of an all-electric heat pump is upgrading the power connection from 1x 35 or 1x 40 Ampere to 3x 25 Ampere to cover the increased electricity consumption(Liander, n.d.; Milieu Centraal, 2018). In houses where a more powerful heat pump is required or if additional appliances are present which require significantly more power, it might even be necessary to upgrade to a 3x 35 Ampere connection (Liander, n.d.).

Milieu Centraal (2018) reported that in order to replace a natural gas boiler in an average Dutch household which consumes 1050 m3 natural an air-source heat pump would require 3150 kWh and a ground-source heat pump would require 2400 kWh. This would mean that on average Dutch households increase their electricity consumption from 3500 kWh to 6000 kWh if no energy saving methods are applied. When energy-saving methods of around 40% are applied the annual electricity consumption would be around 5000 kWh per household. The focus for the all-electric scenario would, therefore, be on the required infrastructure to support the increased electricity demand. This would mean that household power connections and neighbourhood power transmission lines would need to be strengthened. Additionally, the electricity production has to be scaled up to be able to provide sufficient power to cover for the expected increased demand if the majority of households convert to all-electric heating.

The major component of the all-electric system is the heat pump. The electricity infrastructure which is present in the neighbourhood is vital too and will be discussed in the following subchapters. In **Error! Reference source not found.** details on the heat pump are shown. The detailed overview of materials associated with the heat pump can be found in appendix C.

Table 4 Major component of the all-electric system. SCOP = seasonal coefficient of performance, this factor demonstrates the efficiency of heat pump to convert electricity into heat. Meaning 1 kWh of electricity produces 3.5 kWh of heat in case of a SCOP of 3.5. Source Milieu Centraal, 2018

Component	**Main materials**	**Estimated lifespan**	**Comment**
Heat pump	PVC, Steel & copper	15–20 years	SCOP of 3.5

1.1.5. Technology overview – Wind turbines

In the Netherlands, wind energy is gaining momentum in terms of acquiring market share in the energy market. The estimated power production of wind energy was 3.12 billion kWh in 2007 and rose to 9.64 billion kWh in 2017. The electricity was generated by approximately 4200 MW of installed capacity in the same year. The majority of wind turbines were installed on land (3240 MW) (CBS, 2018). The Dutch government plans to install more wind turbines to reach climate change goals for 2030. In the Klimaatakkoord (2019) plans are described to install wind parks in the North Sea with a combined capacity of 11500-14000 MW and 6000-10000 MW on land (Rijksoverheid, 2019).

The two most widely used wind turbine types are direct drive and gearbox wind turbines (van Exter, Bosch, Schipper, Sprecher, & Kleijn, 2018). Gearbox wind turbines have a clear advantage when it comes to the use of critical metals compared to direct drive wind turbines. Direct drive wind turbines consist of large permanent magnets and therefore contain more neodymium, dysprosium and praseodymium. Gearbox wind turbines use less critical earth elements, but require more maintenance due to a greater amount of moving parts. Additionally, gearbox wind turbines are considered having shorter energy payback periods. However, due to the lower maintenance requirements of direct drive turbines they are considered more suitable in off-shore projects (Morris, 2011).

In terms of electricity generation capacity, the average onshore wind turbine in Europe achieves a capacity factor of around 25%. ECN estimated in 2016 that wind turbines installed on land have an annual average of 2500 full load hours in the Netherlands. Wind turbines which are installed offshore achieve higher average capacity factors due to stronger and steadier winds at sea. Their average capacity factors are estimated at around 40%. The full load hours of wind turbines installed offshore were estimated to be 4200 hours by ECN in 2016. These values will be taken into account in the model to estimate the power generation capacity of wind turbines. Power ratings of a wind turbine multiplied with the full load hours would provide the total annual generation capacity of a wind turbine in kWh.

Often the large space requirement of wind turbines is considered to be a disadvantage. However, the world has abundant space for offshore wind projects even when planning has to consider shipping lanes, fishing and bird migrations (Janssen et al., 2012). On the other hand, the downsides of offshore wind projects are the harsh conditions and higher reliability requirements. Even when considering that most offshore wind parks are developed in shallow and intermediate waters with depths up to 45m.

Table 5 Main types of wind turbines. Source Morris, 2011.

Component	**Main materials**	**Estimated lifespan**	**Comment**
Direct drive wind turbine	Concrete, steel & zinc	15–20 years	Easier maintenance offshore
Gearbox wind turbine	Concrete, steel & zinc	15–20 years	Less critical materials

1.1.6. Technology overview – Solar photovoltaic panels

The second sustainable electricity generation technique is solar photovoltaic panels. Their implementation in the energy system has taken a large leap in recent years. From a generation capacity of 38 million kWh in 2007 to 2.1 billion kWh in 2017 (CBS, 2018). The total installed capacity was estimated at around 2.7 GW in 2017. For 2030 an increase to 23 GW of installed solar capacity is required by the Dutch government to comply with environmental ambitions (Rijksoverheid, 2019). By creating profitable legislative support for consumer solar panels the government hopes that at least 50% of the installed solar capacity would be in the hands of consumers. In other words, rooftops of privately owned buildings will be one of the main installation locations for solar panels in the near future.

The report by van Exter et al. (2018) made a distinction between three types of PV panels which could be used to supply electricity through PV panels in the Netherlands. The authors consider silicon panels, thin-film CdTe panels and thin-film CIGS panels. In general thin-film CdTe panels have lowest CO_2 emissions and shorter energy payback times, but the amount of tellurium and cadmium which are used are considerably higher than in the other two types. Their efficiency is usually around 9-11% and costs less than crystalline silicon panels. Crystalline silicon solar panels are the most widely used panels in the world. The monocrystalline variant is highly efficient (up to 21.5% power conversion) and has a relatively long lifespan of 25 years. However, they are very costly and their production process generates a lot of waste due to inefficient silicon wafer production. The polycrystalline counterpart is simpler and less costly, but their efficiency is also lower at around 13-16%. The last category of CIGS panels range in efficiency between 10 and 12% and have the most potential in terms of improving their efficiency (Energy Informative, n.d.).

A typical solar panel consists of an energy generating panel, housing for the panel, an inverter and possibly a solar controller and battery. Critical metals are present in some PV panel types. Indium is present in amorphous silicon and CIGS panels. Gallium is present in CIGS, concentrating photovoltaic (CPV) panels and emerging panel technologies. While these rare metals account for only for a small part of the PV panel volume, their value is significant. Critical metals which were described can mostly be found in the battery pieces which are present between the EVA of the PV panel (Xu et al., 2018). An overview of the materials which are present in each of the PV panel types is provided in Appendix C.

Table 6 Main types of solar panels. Source (van Exter et al., 2018).

Component	**Main materials**	**Estimated lifespan**	**Comment**
C-Si	Copper & silicon	25–30 years	Most widely used
CdTe	Copper & cadmium	25–30 years	Lowest CO_2 emissions
CIGS	Copper, indium & gallium	25–30 years	Most potential for efficiency improvements

1.1.7. Technology overview – Power cables and transformers

The most essential part of the electricity grid is the power grid which connect the electricity generators to the end-user. In the Netherlands, the national high- and low-voltage grids are split between a couple of network operators. These network operators manage maintenance and balancing of supply and demand. The major components which will be included in this thesis are the power cables, transformers and substations as these elements are relevant on the scale of the project.

The electricity network is divided into several subsystems which each have their own characteristic voltage and power characteristics. Divisions between connection, transport and distribution network which is used in this thesis are described in an online manual by Phase to phase (n.d.). According to Phase to phase transformers are placed in the local distribution network which converts power from 10 kV to 400V. These transformers are capable of handling around 250 end-users. Jorge, Hawkins, & Hertwich (2012) provide a LCA of transformers and substations and data which they provide on the 315 kVA transformer closely resembles the transformers used in the local distribution grid. The material data on cables is mainly provided by Nexans (2019), Eland Cables (2019) and Liander (2019). The overview of the cables used can be found in Table 17 (chapter 4.5) and Appendix C.

Table 7 Components of electricity grid. Source (Fant et al., 2020; Phase to phase, n.d.).

Component	**Main materials**	**Estimated lifespan**	**Comment**
Transformers	Copper, steel & concrete	40-50 years	
Cables	Copper, aluminium & plastics	20–50 years	Maintenance requirements vary greatly due to load

1.2. Identification of problem and knowledge gap

The focus of this thesis is on the heating transition and the adaptations which are required to complete the transition from an infrastructural perspective. In the literature review 4 alternative heating techniques are described which are deemed as suitable replacements for natural gas heating. In previous work van der Kooij (2019) described the adaptations which are required on the household scale. Additionally, the question was raised what the consequences would be for the energy infrastructure on the district level. Further research in this field was required according to van der Kooij (2019) as the information about neighbourhood energy infrastructure is relatively scarce in literature. How would the energy demand of the proposed sustainable heating techniques influence the scaling of the energy infrastructure? Furthermore, what would be the expected volume of metals, plastics and rare earth elements which are to be expected if the heating method would be altered?

Taking into account the literature which has been discussed above sufficient research has already been conducted on the design of energy networks, the environmental impact of building materials and various energy generation techniques which could supply sustainable heat and power. However, these studies often only perform a LCA study or provide methods for scaling of heating systems. The aim of this paper is to investigate the heating transition from a larger scale and determine the material requirements of more sustainable heating techniques. By combining material inventory information with spatial energy demand of a city and estimation of future energy system scaling could be achieved. In the end this thesis should provide a recommendation to the municipality of Leiden which sustainable heating could replace natural gas the best in terms of environmental impact associated with the embedded materials.

1.3. Research questions

The main research question which will be answered in this thesis is:

What are the material and energy requirements for upscaling sustainable energy infrastructure?

In order to answer the main research question the following sub-questions are interesting:

1. Which infrastructural changes are required to prepare neighbourhoods for sustainable heating technologies?
2. What are the differences between sustainable heating technologies which could be applied in Leiden?
3. Does scaling to a city level introduce problems regarding infrastructure performance in the chosen technologies?
4. How does the topography of the city influence the choice between sustainable heating alternatives?

2. Methodology

In Figure 1 the general approach for the methodology of this study is described. The information gathered in the literature review with regard to sustainable heating and electricity technologies resulted in a comprehensive technical and material database. Datasets provided by CBS, Kadaster and network operators were combined in order to create a spatial model of the energy infrastructure and energy demands of Leiden. By combining these spatial datasets and the material databases in a Geopandas model the analysis of the heating transition was conducted. A more detailed overview of the code used in the Python model can be found in Appendix A:. In this chapter the model architecture, assumptions and system boundaries will be discussed.

2.1. Model architecture

The model consists of three major parts. The data preparation, scenario-specific calculations and the environmental impact assessment. These three parts are presented in Figure 1**Error! Reference source not found.**. An overview of the Python code which is used in this study is found in Appendix A.

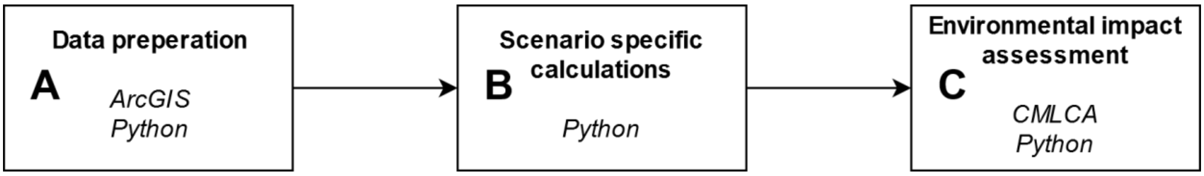


Figure 1 General overview of the model. In part A the data was visually inspected using ArcGIS. Following the inspection, the different data types were combined and prepared for analysis. In part B the main calculations were performed using Python. Each of the scenarios were analysed using a separate and scenario-specific Python file. In part C the environmental impact of the required materials from part B was determined.

Part A:

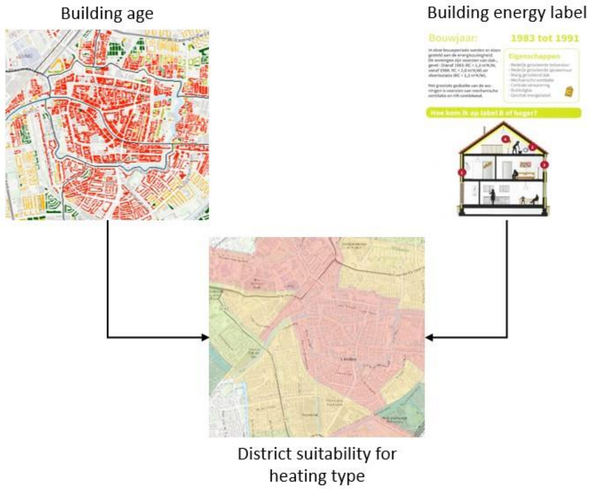


Figure 2 Combination of spatial databases and energy label scoring with regard to building age resulted in the suitability for low-temperature heating for each district.

To use the different datasets provided by the CBS (PC_6_woning) and Kadaster (BAG3D) for this research a unified database had to be build. The CBS database contained information about average energy demand, summed energy demand and number of connections on a 6-digit postal code-level. The database by Kadaster contained information about the building function, geometry and age. Through a spatial join on postal code the layers were combined. A similar spatial join was performed on the district level. In the last step of data preparation, the year of construction was used to determine the suitability for low-temperature heating. The suitability was based on a brochure provided by "*Woningwijzerwinkel*" (Woningwijzerwinkel Energy LabelsAppendix C:. The exact division according to building age can be found in subchapter 2.5 bellow. The database which was created will be the starting point for all calculations in the model (Figure 2).

The databases by Liander provided spatial information about the low-, medium-, and high-voltage cables and low- and high-pressure gas pipes in Leiden. The power cables mostly contained information about their material content. Applying the *.length* function in Geopandas allowed for determining the exact length of the power infrastructure which was present in each district. The same principle was applied to natural gas infrastructure. However, the materials were unknown. An estimation based on the length of each pipe segment was used to determine the material of the pipes as described in Appendix B:.

Part B:

The heating demand of the districts was provided in cubic metres of natural gas and kWh electricity. The cubic metres of natural gas had to be converted into kWh. The formula used was:

$$Heating\ demand\ [kWh] = \left(\frac{Gas\ demand\ [m3] * CV}{3.6}\right) * \eta\ boiler$$

CV = calorific value of natural gas. CV = 35.17 MJ/m^3

η boiler = efficiency rating of HR boiler HR boiler efficiency = 90%

For each of the heating techniques the estimated energy demand of the households had to be determined. These calculations were different for each energy technique, but followed the same principle. The formula for low-temperature district heating was:

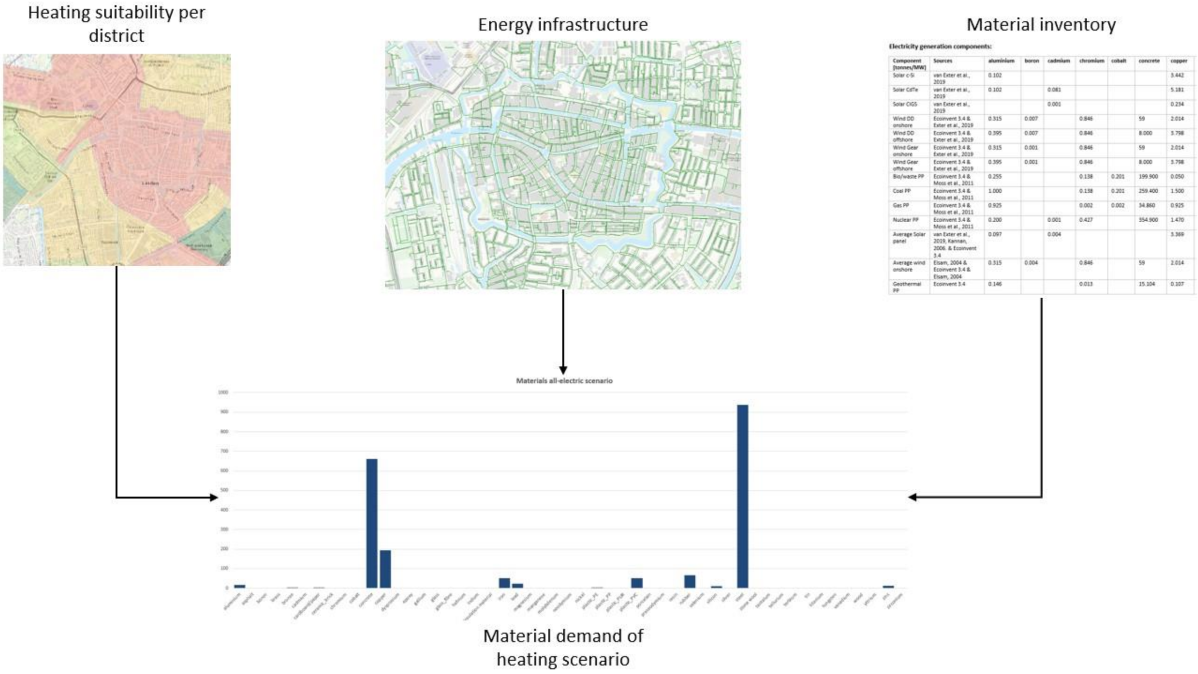
$$Heating\ demand\ household\ [kWh] = \frac{Heating\ demand\ [kWh]}{\eta\ prod * \eta\ trans * \eta\ house}$$

η prod = production efficiency of heating type. For low-temperature district heating (LTDH) this is 100% as excess heat is gained from industry.

η trans = transport efficiency of heating type. For LTDH this was 15% heat loss due to general transport in high pressure pipes and 0.25% heat loss per km in low pressure pipes.

η house = The specific efficiency of the household equipment. For LTDH this was the SCOP of 3.5.

The cumulative energy demand of the city, length of each infrastructure type and amount of in-house equipment required were coupled to the material inventory database (Appendix D:). The database contained the materials which were required per 1 MWh installed capacity, 1 km of cable or pipe or 1 unit of in-house equipment (Figure 3).



Electricity generation components:

Component (tonnes/MW)	Sources	aluminium	boron	cadmium	chromium	cobalt	concrete	copper
Solar c-Si	van Exter et al., 2019	0.102						3.442
Solar CdTe	van Exter et al., 2019	0.102		0.081				5.181
Solar CIGS	van Exter et al., 2019			0.001				0.234
Wind DD onshore	Ecoinvent 3.4 & Exter et al., 2019	0.315	0.007		0.846		59	2.014
Wind DD offshore	Ecoinvent 3.4 & Exter et al., 2019	0.395	0.007		0.846		8.000	3.798
Wind Gear onshore	Ecoinvent 3.4 & Exter et al., 2019	0.315	0.001		0.846		59	2.014
Wind Gear offshore	Ecoinvent 3.4 & Exter et al., 2019	0.395	0.001		0.846		8.000	3.798
Bio/waste PP	Ecoinvent 3.4 & Moss et al., 2011	0.255			0.138	0.201	199.900	0.050
Coal PP	Ecoinvent 3.4 & Moss et al., 2011	1.000			0.138	0.201	259.400	1.500
Gas PP	Ecoinvent 3.4 & Moss et al., 2011	0.925			0.002	0.002	34.860	0.925
Nuclear PP	Ecoinvent 3.4 & Moss et al., 2011	0.200		0.001	0.427		354.900	1.470
Average Solar panel	van Exter et al., 2019, Kannan, 2006. & Ecoinvent 3.4	0.097		0.004				3.369
Average wind onshore	Elsam, 2004 & Ecoinvent 3.4 & Elsam, 2004	0.315	0.004		0.846		59	2.014
Geothermal PP	Ecoinvent 3.4	0.146			0.013		15.104	0.107

Figure 3 Combination of heating suitability, spatial energy infrastructure databases and the material inventory resulted in the material demand for each of the heating scenarios.

Part C:

The last step of the analysis combines the material inventory with an environmental database from Ecoinvent 3.4. The impact database is based on CML 2001 Baseline and has information on the impact in nine categories. For the final analysis, only the climate change impact in CO_2 equivalent and the abiotic resource depletion in antimony equivalent are used. Multiplying the required materials with their specific impact provides a database with the embedded impact of the required materials. The database with the associated impacts is exported to Excel (Figure 4).

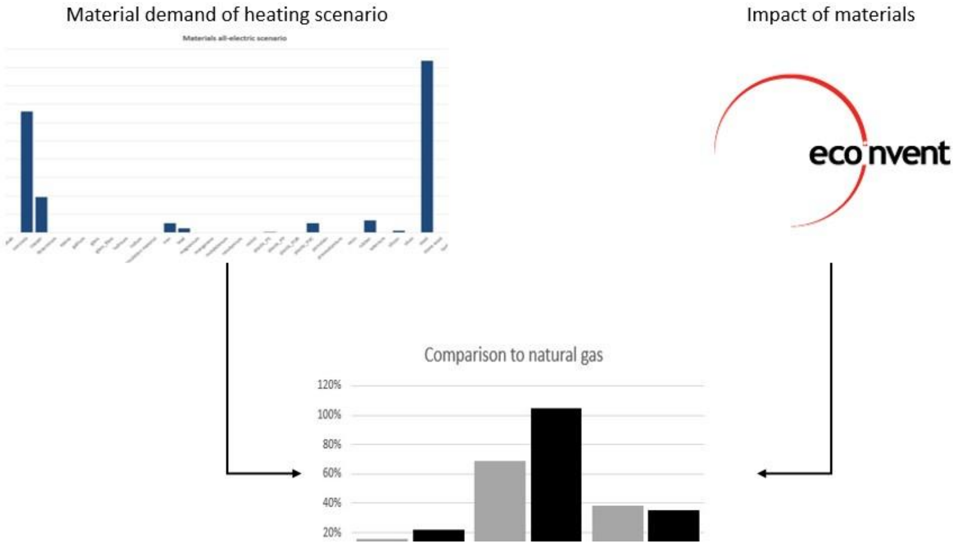


Figure 4 The material demand dataset generated in the previous step was multiplied with the environmental impact per kg.

2.2. System boundaries

The current and proposed future heating situation in the Netherlands was modelled with certain restrictions to ensure a workable model. The Dutch situation was replicated by establishing both geographic and technological boundaries. Firstly, the geographic boundary of the model is the municipality of Leiden.

Secondly, technological boundaries were chosen based on the municipal heating policies of Leiden and The Hague. Both of which were documented in the *"Warmtevisie"* (2017) and *"Scenario's voor de warmtetransitie in Den Haag"* (2017) respectively (Gemeente Den Haag & CE Delft, 2017; Gemeente Leiden, 2017). These documents mentioned the following sustainable heating techniques: low-temperature district heating, high-temperature district heating, heat pumps and sustainable gas or biomass. Figure 5 visualises the scope of the research. Adaptations which are applied inside the houses, apart from installing of the main heater, are deemed out of the scope of the research as these adaptations were already investigated by Van der Kooij (2019). This designates the houses as a black box which only consume energy, but energy saving measures are applied to simulate the possible increase in energy efficiency. This analysis aims to determine the material intensity of the energy infrastructure; therefore, the system includes the connection to a house up to the point where the energy is generated.

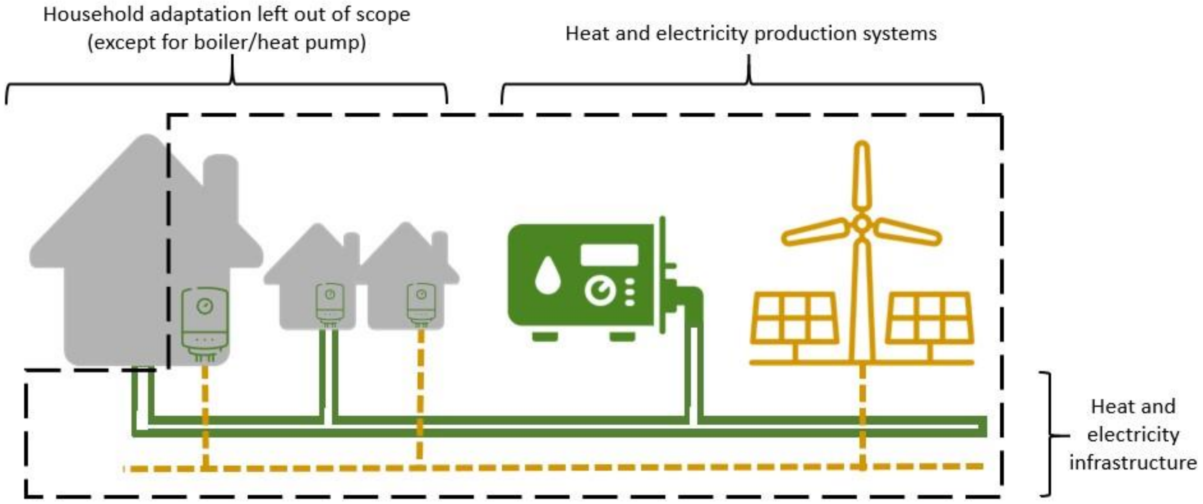


Figure 5 Scope of the research. Adaptations which are applied to the houses, such as improving insulation and ventilation, are deemed out of the scope of the research. Only the installation of a boiler, heat exchanger or heat pump is taken into account. This designates the houses as a black box which only consumes energy, but energy saving measures are applied to simulate the expected increase in energy efficiency. This analysis aims to determine the material intensity of the energy infrastructure; therefore, the system includes the connection to a house up to the point where the energy is generated.

To investigate the material impact of different heating techniques and how they are influenced by the cities characteristics the analysis is split into two parts. First, the heating alternatives are being compared exclusively on their required materials and embedded carbon content of the materials. This part of the analysis does not include the suitability of a heating technique for a specific district. It determines what the impact of changing the heating supply would mean in terms of materials and environmental impact. The second part attempts to include district characteristics to choose the correct heating alternative for each district of the city. Building age of a district is the main driving force for the choice of heating alternative.

2.3. Model assumptions

In order to simplify some aspects of the energy system dynamics or close gaps within the data, some assumptions had to be made. The following subchapter will describe the most important assumptions which were made to create a functional model.

- Adaptations for electricity and heating demand for future scenarios. The adaptations mentioned below are taken into account when calculating the total electrical and heating demand of a district.
  - Netbeheer Nederland (2017) report an expected efficiency gain in heating demand of 15%. An efficiency gain of 25% in electricity demand is reported.
  - Population growth between 2019 and 2050 is expected to be 7.2%. In Leiden this would mean approximately 4800 new households.
- The average age of all houses inside the district is used to determine an optimal heating technique for the whole district. Normally there could large diversity between the heating techniques which would be appropriate for each specific house.
- The location and length of existing cables and pipes are used in the future scenarios. Drawing of new cables or pipelines is not included in this thesis due to modelling complexity. However, the addition of cables and pipelines is taken into account with the addition of households due to population growth. The infrastructure present in an existing district (Stevenshof) which has a similar size (4800 households) as the expected growth is added to the future scenarios. This is about 11% of the total length of installed pipes and cables.
- Trench works required for the installation of cables and pipes are left out of scope due to insufficient data being available on the required materials.
- Table 8 shows electricity generation mixes which are used in the model. These mixes are used to determine the number of electricity generators which are required.
- The ratio of wind turbines installed onshore and offshore is determined by CBS Statline (2018) for baseline. The baseline wind ratio was established at 20% offshore and 80% onshore. For the future scenarios the Netbeheer Nederland (2017) calculated the ratio. The future wind ratio was established at 70% offshore and 30% onshore.
- Distance between wind turbines was established at 500 meters. This distance was used to calculate the cable length required in wind parks. Additionally, the average distance to offshore wind parks was set at 32 km. This is equivalent to the average distance of Dutch offshore wind parks.

Table 8 Electricity mixes used in the scenarios. Baseline is based on CBS Statline data from 2018. Future electricity mix data is based on (Netbeheer Nederland, 2017). All of the numbers are reported in percentages.

Generator type [%]	Oil	Coal	Natural gas	Biomass	Biogas	Nuclear	Geo-thermal	Wind	Solar	Hydro	Total renewables
Baseline (2018)	3.4	24	50.7	4.1	0	3.1	2.5	9.3	2.8	0.1	21.9
Future	0	0	9	7	11.5	0	1.5	46	25	0	91

- The dimensions of the cables and pipes used in the model are presented in detail in Appendix B:. The natural gas pipes were divided into five size categories according to their pressure or length. The same principle applied to district heating pipes. For electrical cables the division was based according to voltage and configuration of the cables.
- To determine the power which is generated by each power generator or factory and estimation of the full load hours per year was made. Expected full load hours (or capacity factor) for each technology to estimate the required installed capacity. Table 9 displays the full load hours used in the model. The full load hours are based on Netbeheer Nederland (2017).

Table 9 Full load hours. Assumption made on full load hours of electricity generators.

Technology	Hours/year	**Technology**	Hours/year
Biomass	2000	Wind offshore	4500
Biogas	500	Wind onshore	3000
Natural gas	2000	Solar PV	1000
Nuclear	7800	WKK biogas	500
Hydro	3200	Geothermal	6500
Biogas factory	2000	Household boiler	2000

- In order to enhance the visualisation of the results, the materials were divided into groups with resembling elemental characteristics. The five groups which were made are metals, plastics, rare earth elements, metalloid & non-metals and others. The metal category is relatively large compared to the other groups, but a large diversity in embedded metals is to be expected in the energy sector. The included materials are presented in Table 10.

Table 10 Material categories. PE = Polyethylene, PP = polypropylene, PVC = Polyvinyl chloride.

Metals			Plastics	REE	Metalloid	Others
Aluminium	Indium	Silver	Epoxy	Dysprosium	Boron	Asphalt
Bronze	Iron	Steel	PE	Neodymium	Selenium	Cardboard/paper
Cadmium	Lead	Tantalum	PP	Praseodymium	Silicon	Concrete
Chromium	Lithium	Tin	PVC	Terbium	Tellurium	Glass
Cobalt	Magnesium	Titanium	Resin	Yttrium		Glass fibre
Copper	Manganese	Tungsten				Graphite
Gallium	Molybdenum	Vanadium				Porcelain
Hafnium	Nickel	Zinc				Stone wool

2.4. Comparing heating alternatives

In order to review each of the heating alternatives which are discussed in this thesis, the city of Leiden was chosen to facilitate as case study area for the comparison between the heating technologies. Basic characteristics of the comparative environment are described in Table 11. The goal of the comparison is to determine the material demand of the heating transition in a typical Dutch city if all of the households would convert to a specific heating method. For the purpose of the comparison the suitability of the houses for a specific heating alternative is not taken into account.

Table 11 Primary characteristics of the city of Leiden.

Parameter	Value [unit]
Number of households	67735
Average electricity demand per household	2500 [kWh]
Average heating demand per household	8200 [kWh]
Average year of construction	1929

The heating and electricity systems have been divided into two subsystems. The first subsystem is the production of the heat or electricity carrier. This could be natural gas, biogas, hot water or electricity. Efficiencies of each subsystem are a generalisation and would likely vary more in practice depending or technology age. District heating systems transport hot water and thus the hot water will lose some of its warmth along the way. For transportation of gas and electricity it is assumed that no losses occur. An overview of the five different scenarios is provided in Table 12.

Table 12 Overview of the characteristics of each heating alternative. The production-consumption distance is based on the distance to the city of Leiden. Heat transport and household system efficiencies are based on (CE Delft, 2019b; Netbeheer Nederland, 2017; TU Delft, 2015; Xie, Wang, & Mai, 2019)

Heating scenario	**Infrastructure present in district?**	**Heat production**	**Production-consumption distance**	**Transport efficiency**	**Household system**	**Household system efficiency**
Natural gas	Gas and electricity	Natural gas drilling	200 km	99.5 %	Natural gas boiler	90 %
Biogas	Gas and electricity	Biogas factory	50 km	99.5 %	Biogas boiler	90 %
Low-temperature district heating	Heating pipes and electricity	Residual industrial heat	50 km	85 %	Heat exchanger	425 %
High-temperature district heating	Heating pipes and electricity	Residual industrial heat	50 km	72.5 %	Heat exchanger	425 %
All-electric	Electricity	Renewable energy mix	40 km	96 %	Heat pump	350 %

The second subsystem is the transport of the heat or energy carrier to the city where it is required. These values are based on expectations where specific industry or energy generators could be located in the Netherlands. Natural gas would be produced in Groningen. Biogas and high-temperature residual heat would be produced in industrial areas such as the harbour of Rotterdam. Low-temperature residual heat would be extracted from more local sources such as datacentres and supermarket cooling, and therefore the transport distance is a little bit smaller. The renewable energy mix would mainly utilize wind turbines and solar panels so the distance to the nearest wind turbine park at sea was chosen. All of the production-consumption distances are relative to Leiden.

2.5. Heating alternatives applied in practice

The second part of the analysis is focussed on practical implementation of the heating alternatives discussed in chapter 0. Where the first part did not include suitability of houses for low-temperature heating an attempt is made to incorporate these characteristics in this comparison. Suitability for low-temperature heating is determined by building type and mainly wall and window insulation and passive ventilation. In general, houses which are constructed after 1992 have good insulation and low passive ventilation and therefore the space heating demand of these buildings is low. In older houses, insulation and ventilation are subpar which could make them unsuitable for low-temperature heating. The relation between energy label and building age is based on information by Woonwijzerwinkel in Appendix B. Additionally, the building type is important. Multi-unit dwellings such as flats and apartment buildings are more energy-efficient per dwelling compared to single detached homes. Despite building type and thus insulation and ventilation are very specific for each building a generalisation can to be made. The quality of the insulation and ventilation will be based on the energy label, which is roughly based on the building age and type. For this thesis, a division in building heating characteristics is made into four categories.

1. Suitable for high-temperature heating only. These are the oldest buildings. Their construction year is before 1945. These buildings typically have energy label G. They have poor insulation and good natural insulation. It would require major, costly adaptations to improve their energy label.
2. Suitable for high-temperature heating with minor heat savings. These buildings are built between 1946 and 1974 and usually have energy label E or F. These buildings have slightly improved insulation on the roof, but the walls and windows remain poorly insulated. Natural ventilation is still present in these buildings.
3. Suitable for low-temperature heating with minor heat loss. These buildings are built between 1975 and 1991 and usually have energy label D or C. Average insulation is present in the walls, windows, floors and roofs. Natural ventilation occasionally needs to be assisted by mechanical ventilation. These buildings are suitable for low-temperature heating, but require an additional boiler or heat pump which could increase heating capacity during the peak loads.
4. Suitable for low-temperature heating. These buildings are the newest and constructed after 1992. Their energy label is B or better. Good insulation is present in these houses and ventilation is almost completely mechanical. Buildings in this category can be heated by low-temperature heating without the need for an additional boiler or heat pump for peak loads.

The division of houses which are suitable for low-temperature heating and houses which are not leads to the integration of different heating alternatives within the same city. There are three different sustainable heating systems which can be applied to the city. First is heating by a combination of high- and low-temperature district heating. Second is heating by biogas and heat pumps where the houses suitable for low-temperature heating are heated by heat pumps and the rest by biogas. The last alternative is all-electric. In this scenario, all of the houses will be heated by heat pumps. The baseline scenario, which is heating by natural gas, will be compared to the three proposed future scenarios and thus the total number of scenarios applied to Leiden is four.

2.6. Description of data

The GIS model which was created for this research had to process both regular and geographic datasets. To enable the model to process both of these datasets Python was used. ArcGIS mainly served as a primary visual inspection of the datasets, but it was also utilized to generate maps which can be found in the results section of the thesis. Spyder with Python 3.7 was used as the main modelling environment and served as the modelling and calculation software. A description of the datasets which were used in the model can be found in Table 13Table 13 below.

Table 13: Overview of spatial datasets.

Dataset name	**Information**	**Geometry type**	**Source**
PC6_woningen	Estimation of energy usage per postcode area Number of connected dwellings at postcode level	Polygon	(CBS, 2014)
BAG_3D	Building age and type	Polygon	(Kadaster, n.d.)
LS_Leiden	Identifying low-voltage cables	Line	Liander (2019)
MS_Leiden	Identifying medium-voltage cables	Line	Liander (2019)
HS_Leiden	Identifying high-voltage cables	Line	Liander (2019)
HD_Leiden	Identifying high-pressure natural gas pipes	Line	Liander (2019)
LD_Leiden	Identifying low-pressure natural gas pipes	Line	Liander (2019)

The main data layer for the geodataframe was the PC_6_woningen data layer. This layer contained information on natural gas usage, electricity usage and the number of connected dwellings at zip code level. This layer is the main information source for estimating the electrical and heating demand for buildings in the area. Natural gas usage was presented in cubic metres of natural gas. This information had to be converted to kWh in order to estimate the thermal demand of a building if they are not heated by natural gas. Through the application of Boyle’s law and the calorific value of natural gas (35.17 MJ/m3), the energy content of cubic metres of gas was determined. An average natural gas boiler efficiency of 90% has to be taken into account to determine the heat demand of the building (CE Delft, 2019b). The other datasets, provided by Liander, contain information about the cables and pipelines present in the case study areas. Medium- and high-voltage cable datasets contained information about materials and cable lengths. However, for the low-voltage cables, the application of the *.length* function of Geopandas was used to determine the length of cables.

The next step of the analysis is to combine the material inventories acquired in chapter 2 with the data from the geodatabases. The material inventories were loaded into the Python file as Panda-dataframes to enable simple extraction of the data. Further description of the composition of the Python code can be found in appendix A.

3. Results

3.1. Characteristics within districts

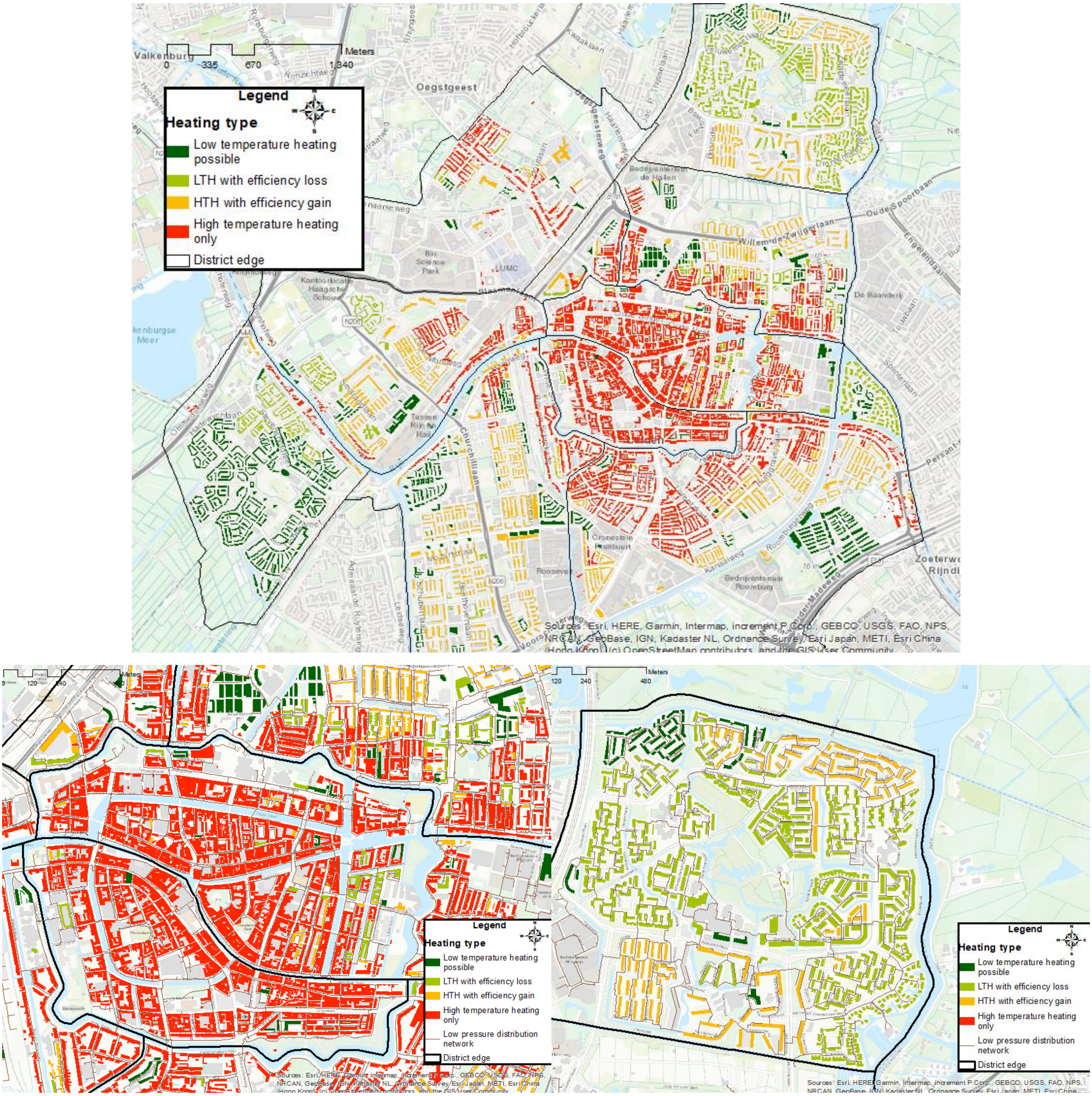


Figure 6 Suitability for low-temperature heating by building age. Top: complete overview of Leiden. Left: the older inner-city districts "Binnenstad – Noord" and "Binnenstad – Zuid". Right: newer district "Merenwijk".

In Figure 6 the suitability for low-temperature heating according to building age is displayed. As mentioned in chapter 2.5 the buildings in this model are categorised. Buildings constructed after 1974 could be heated by low-temperature heating. Buildings which were built before 1974 are deemed unsuitable for low-temperature heating. The top map shows that the majority of the inner-city districts are unsuitable for low-temperature heating. The districts towards the edge of the city are younger. The houses in these outer districts are better insulated and therefore more suitability for low-temperature heating.

The lower-left map of Figure 6 zooms in on the old city centre. The buildings, grouped by postcode, are mostly built before 1900 and therefore possess poor energy labels. Insulating of these structures would require major renovation and upgrading to energy label D is often not possible. According to the information presented in the literature review the suitable heating techniques are natural gas, biogas and high-temperature district heating. Therefore, the majority of the city centre requires extensive low-pressure gas or hot water distribution networks.

In the lower right part of Figure 6, a relatively new district called "Merenwijk" is displayed. All of the buildings are built after 1974. According to their age these buildings should be suitable for low-temperature heating. It is advisable that these districts are provided with low-temperature heating techniques such as low-temperature district heating and heat pumps in order to limit the energy consumption. In such districts where low-temperature heating is possible it would be advisable to remove natural gas pipes and only utilise district heating or all-electric heating.

By aggregating the structures within a district and determining an average district age the most suitable heating temperature of a district is determined. The suitable heating types of each district are shown in Figure 7.

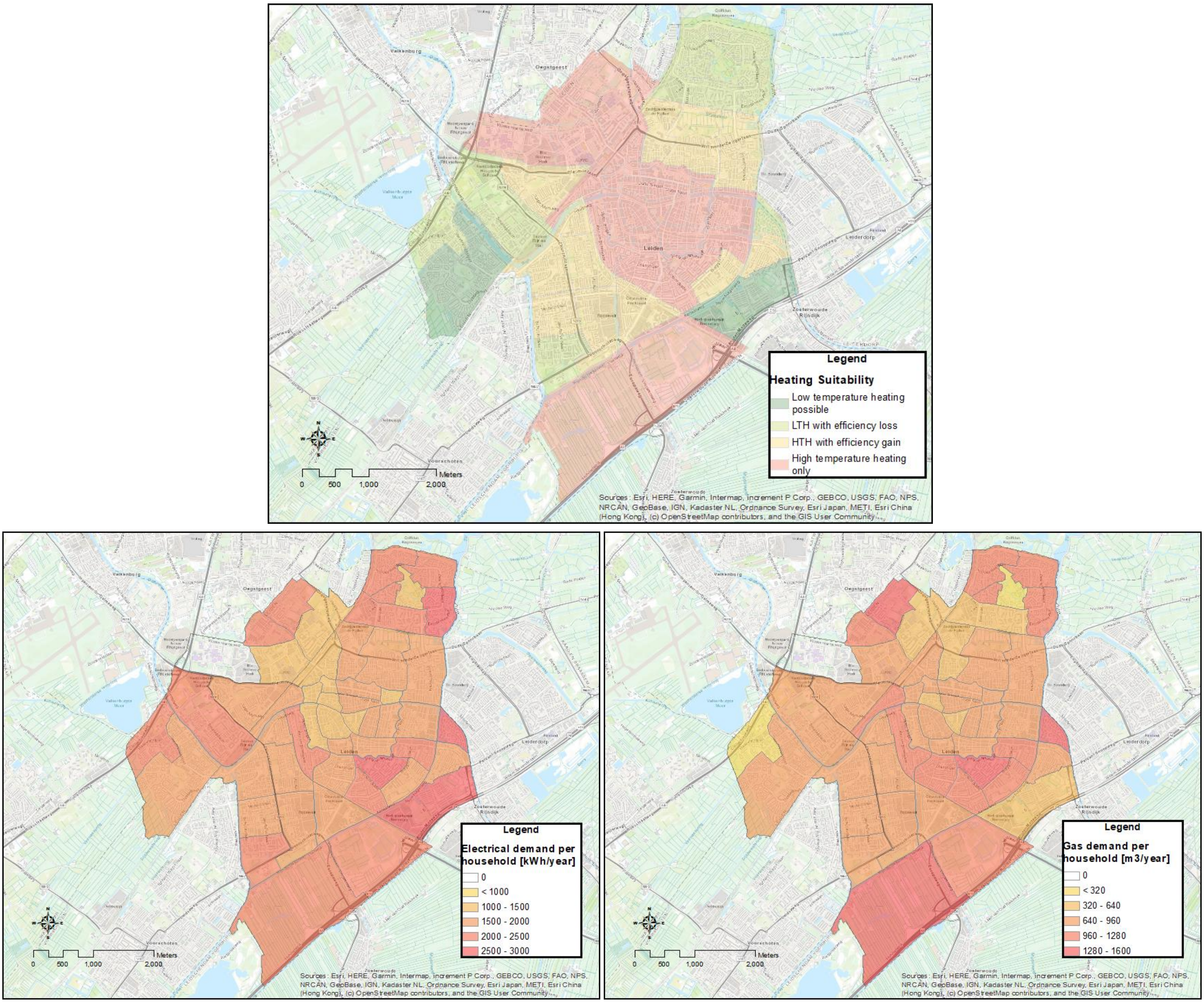
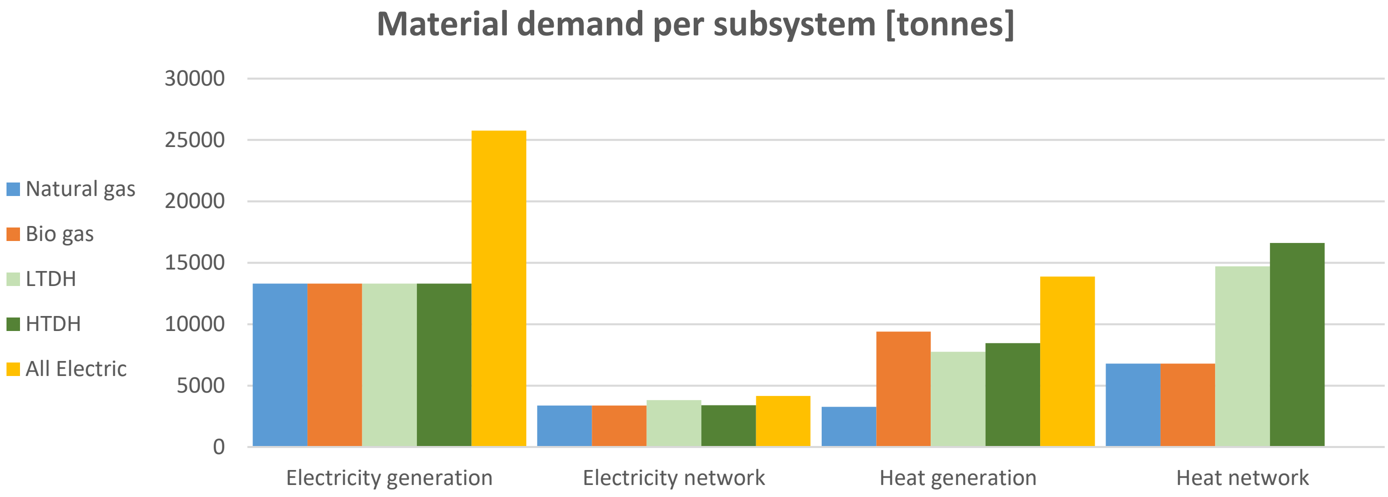
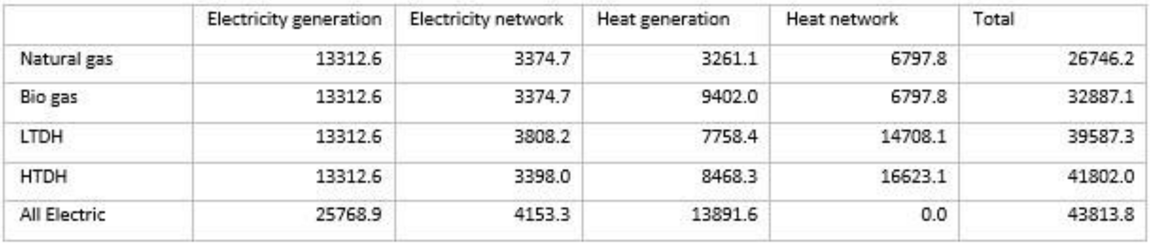


Figure 7 Baseline characteristics of the city district in Leiden. Top: the suitability for high- or low-temperature heating. Mainly based on building age within the district. Bottom left: The electricity demand per household within the district. Bottom right: The gas demand per household within each district. These maps are generated through joining of the PC_6_woning and district datalayers (Table 13).

3.2. Results of heating technique comparison





	Electricity generation	Electricity network	Heat generation	Heat network	Total
Natural gas	13312.6	3374.7	3261.1	6797.8	26746.2
Bio gas	13312.6	3374.7	9402.0	6797.8	32887.1
LTDH	13312.6	3808.2	7758.4	14708.1	39587.3
HTDH	13312.6	3398.0	8468.3	16623.1	41802.0
All Electric	25768.9	4153.3	13891.6	0.0	43813.8

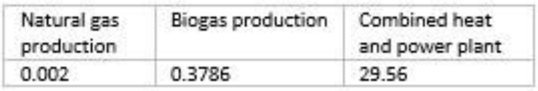
Figure 8 Material demand per subsystem of the energy infrastructure.

If the proposed heating techniques would be applied to the city of Leiden regardless of the suitability for the heating type the natural gas scenario is leanest on materials with approximately 26746 tonnes. The all-electric scenario is the most material intensive at approximately 43814 tonnes. When the different subsystems of the energy infrastructure are examined more closely distinct features of each heating alternative can be found. Natural gas heating and biogas heating are lean on materials as the technology is relatively simple whereas the all-electric alternative is more complex and thus more material intensive. District heating is relatively material intensive due to the insulation requirements for transporting the hot water.

The material demand categorised by subsystem of the energy infrastructure as displayed in Figure 8 shows an expected pattern. The electricity generation subsystem is similar for all heating alternatives except all-electric. This is explained by the increased electricity demand due to electrification of heating. In the electricity network subsystem LTDH and all-electric display are slightly more material intensive due to upgrading of the household connection (1x 35A or 40A to 3x 25A or 35A). The upgraded household connection is required to enable sufficient power transport to the houses for the slightly more powerful heat exchanger in case of LTDH and the heat pump in case of all-electric.

The results in the heat generation subsystem are based on two factors. The mass of heat producer (natural gas pumping rig, biogas production plant or CHP plant) (Table 14) and the mass of the in-house equipment (HR boiler, heat exchanger and heat pump) Figure 9. In the last subsystem the cumulative mass of the heating network is given. Natural gas and biogas alternatives have the same values as the network configuration is exactly the same. The district heating alternatives have a higher cumulative mass as the steel pipes are thicker and the insulating plastic layer is relatively thick too. In case of the all-electric scenario there is no mass as all energy is transported via the electricity grid.

Table 14 *Mass per MW installed capacity. Source: Ecoinvent 3.4*



Natural gas production	Biogas production	Combined heat and power plant
0.002	0.3786	29.56

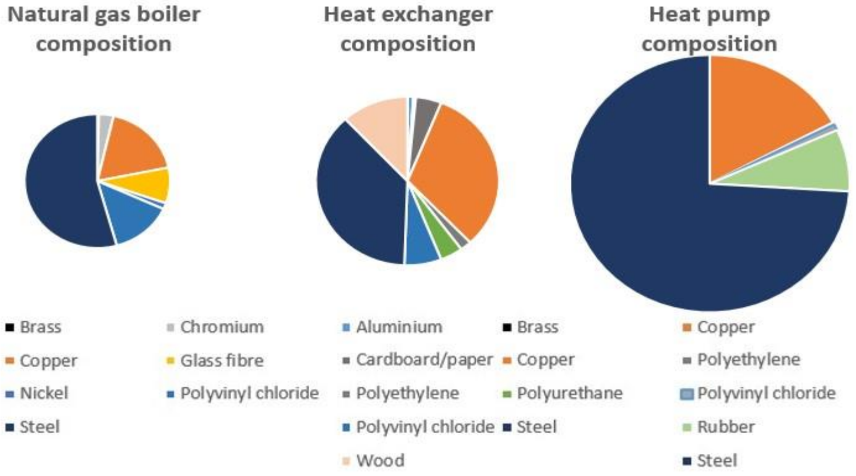
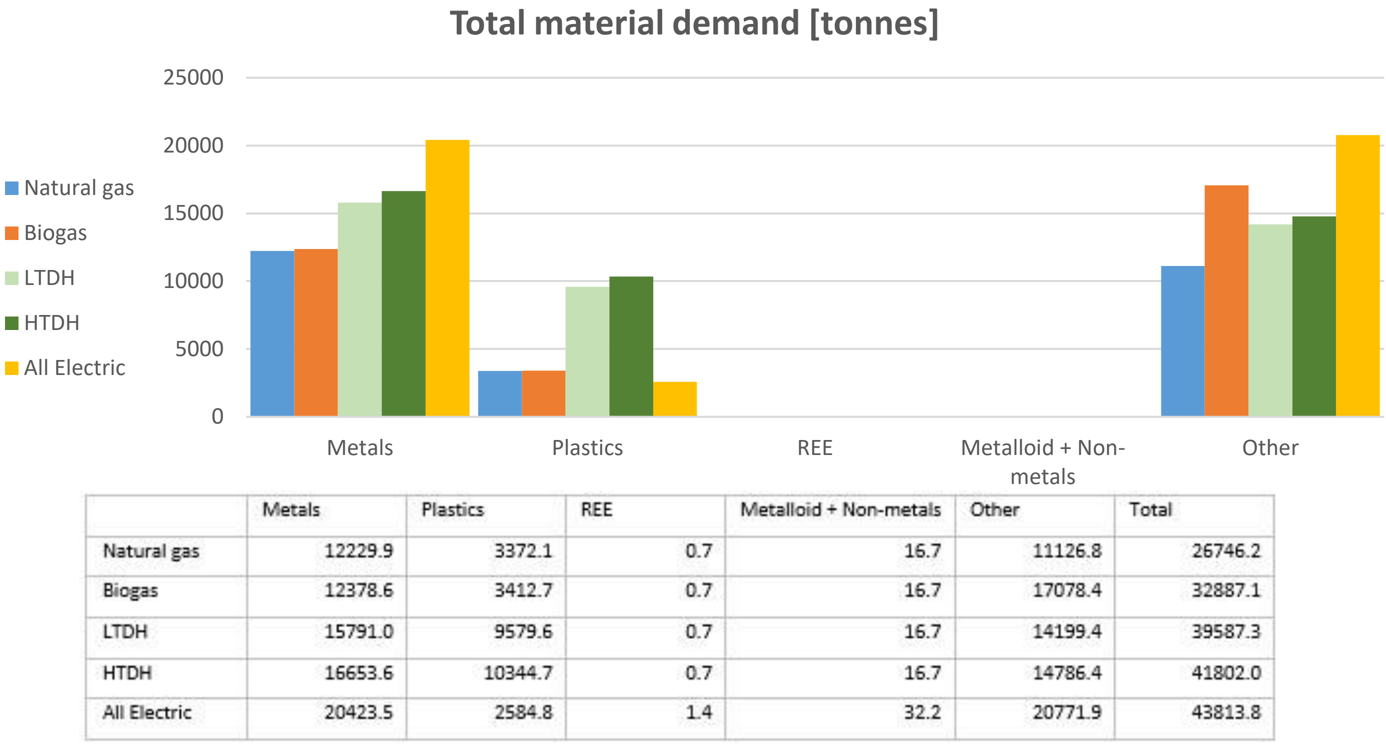


Figure 9 Material composition of the in-house heating appliances. Total mass of the gas boiler is 46.3 kg, total mass of the heat exchanger is 67.5 kg and the total mass of the heat pump is 205.3 kg.

The materials which are required the most in all of the scenarios are bulk materials like concrete and steel. These are mostly present in the power plants and pipelines. There is a considerable demand for PVC as this is used as pipe material in the natural gas and biogas scenarios and PE as insulation material for the district heating pipes. In this comparison the demand for REE is still relatively low as the energy mix used in this scenario is based on 2018 (CBS, 2019).

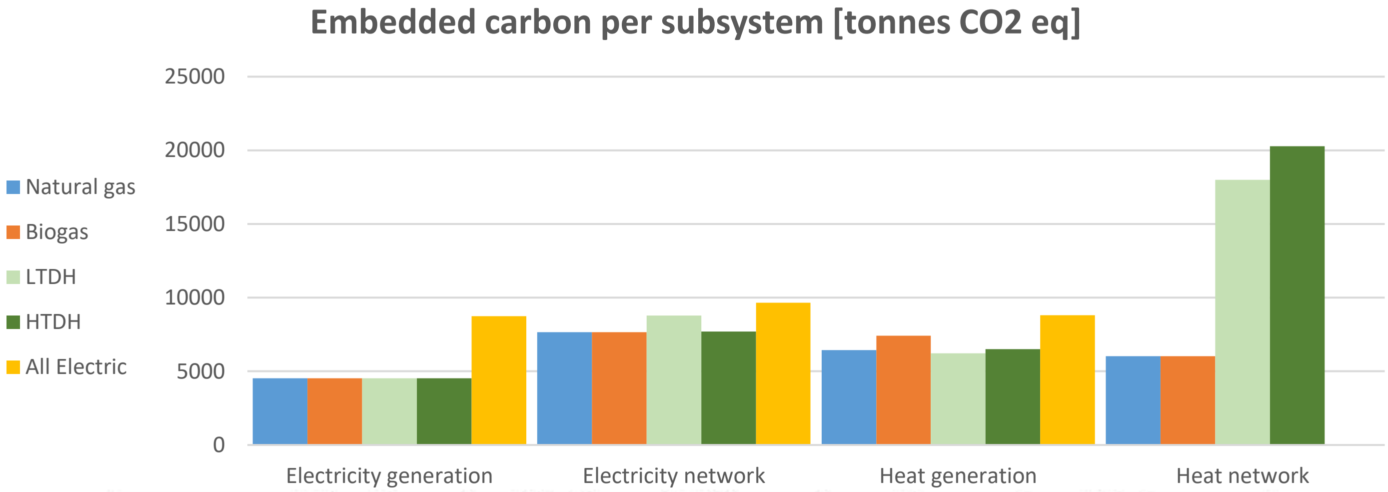


	Metals	Plastics	REE	Metalloid + Non-metals	Other	Total
Natural gas	12229.9	3372.1	0.7	16.7	11126.8	26746.2
Biogas	12378.6	3412.7	0.7	16.7	17078.4	32887.1
LTDH	15791.0	9579.6	0.7	16.7	14199.4	39587.3
HTDH	16653.6	10344.7	0.7	16.7	14786.4	41802.0
All Electric	20423.5	2584.8	1.4	32.2	20771.9	43813.8

Figure 10 Total material demand per heating technique.

3.2.1. Embedded climate change impact of materials

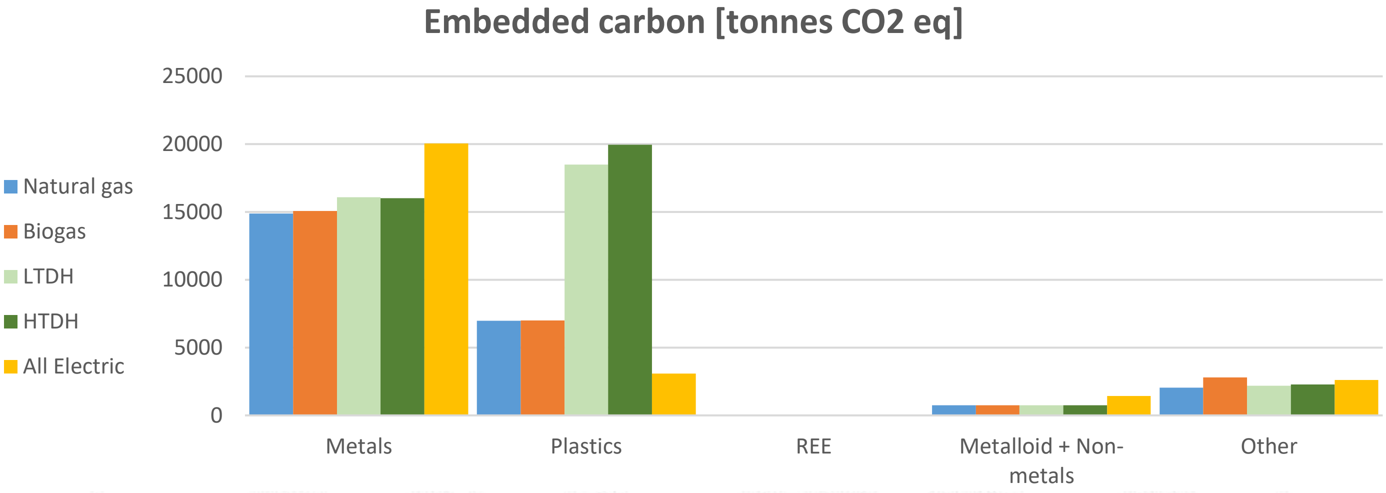
The embedded carbon results show a similar pattern compared to materials embedded (Figure 11). There are a few outliers. The natural gas, biogas and all-electric scenarios score much closer together than compared to just material mass. District heating scenarios score worse. The main reason for the district heating scenario to score worse is the plastics which are required for pipe insulation.

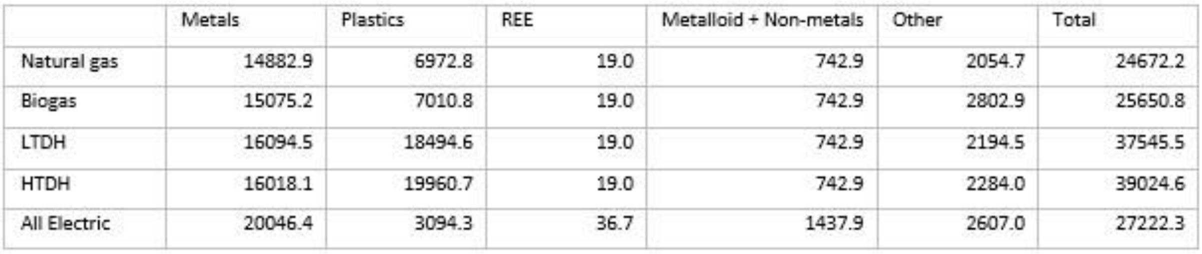


	Electricity generation	Electricity network	Heat generation	Heat network	Total
Natural gas	4520.4	7669.0	6452.4	6030.4	24672.2
Biogas	4520.4	7669.0	7431.0	6030.4	25650.8
LTDH	4520.4	8795.9	6230.1	17999.1	37545.5
HTDH	4520.4	7712.6	6508.8	20282.8	39024.6
All Electric	8750.0	9658.1	8814.2	0.0	27222.3

Figure 11 Total embedded CO_2 emissions per subsystem of the energy infrastructure.

The embedded CO_2 content per material group of the energy infrastructure shows a similar pattern to the total mass required per material group (Figure 12). The major material groups which have a high impact are the metals and plastics. The increase in contribution of the metalloid & metals group is also considerable. This is mainly caused by silicon present in solar PV panels. The others category is relatively small as concrete was a large factor in terms of mass, but its embedded carbon content is relatively low.



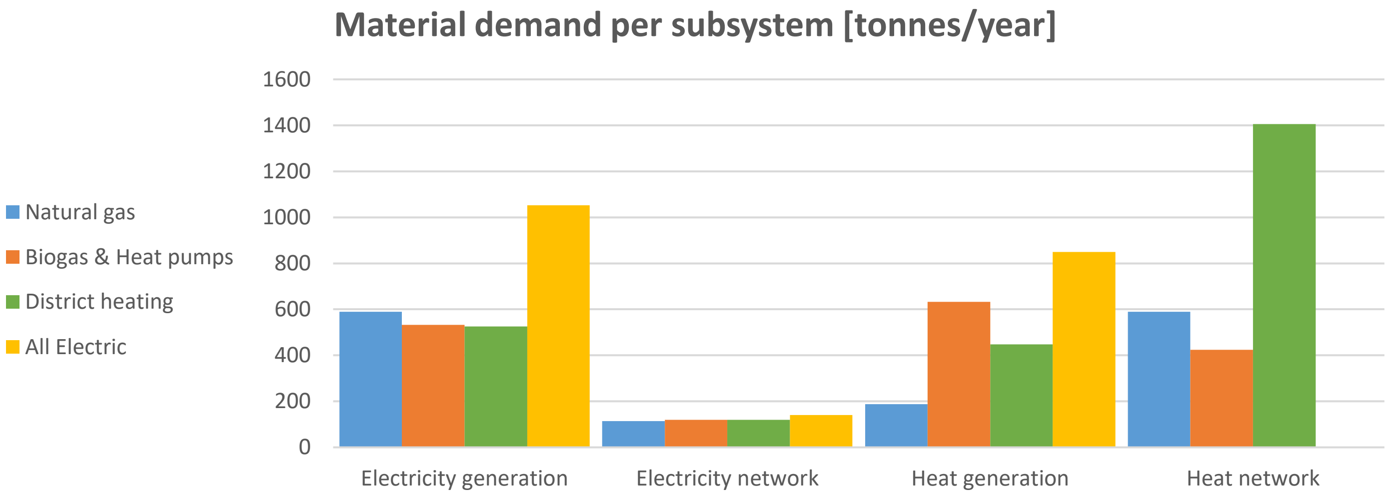


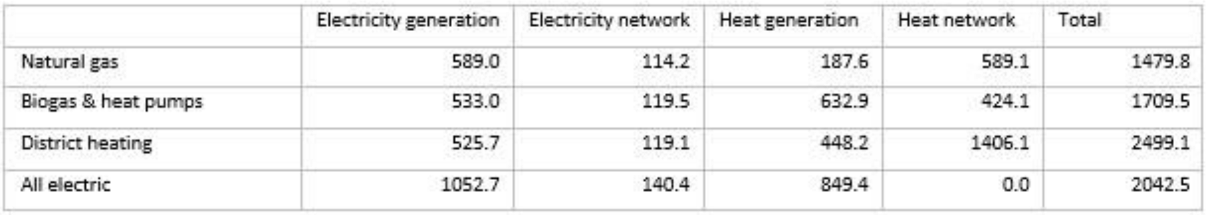
	Metals	Plastics	REE	Metalloid + Non-metals	Other	Total
Natural gas	14882.9	6972.8	19.0	742.9	2054.7	24672.2
Biogas	15075.2	7010.8	19.0	742.9	2802.9	25650.8
LTDH	16094.5	18494.6	19.0	742.9	2194.5	37545.5
HTDH	16018.1	19960.7	19.0	742.9	2284.0	39024.6
All Electric	20046.4	3094.3	36.7	1437.9	2607.0	27222.3

Figure 12 Total embedded CO_2 emissions per heating technique.

3.3. Results of heating techniques applied in practice

In this part of the analysis the absolute materials which were required for construction of the energy infrastructure are adjusted for the lifespan of the components (provided in the literature review). The figures given in this subchapter are thus reflecting approximately how much materials would be spent per year to maintain the energy infrastructure. These figures are then compared to the expected emissions of the heating system.



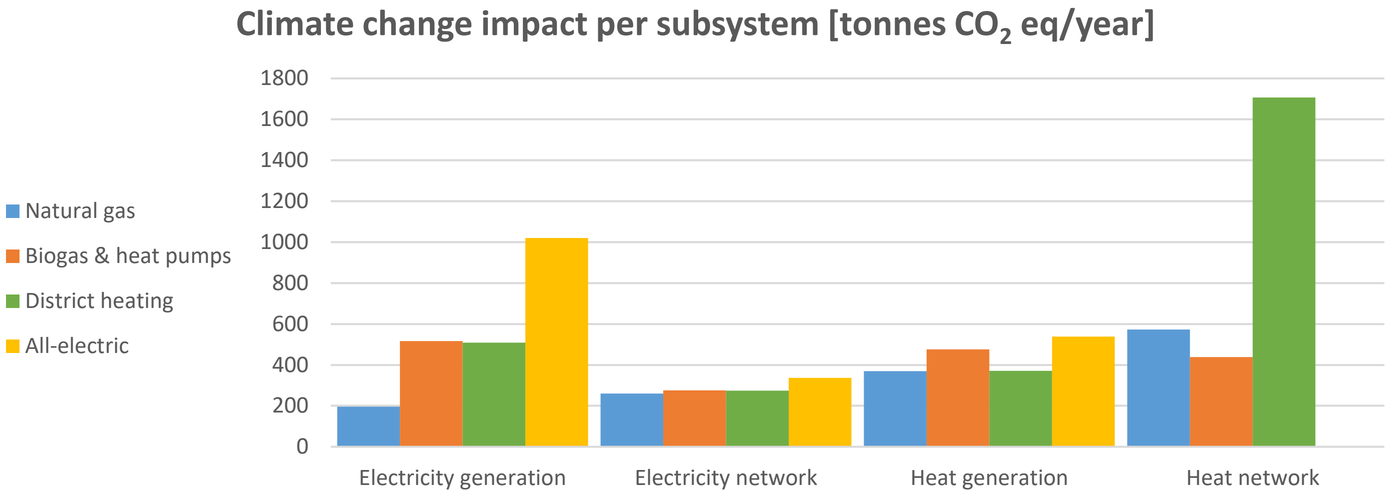


	Electricity generation	Electricity network	Heat generation	Heat network	Total
Natural gas	589.0	114.2	187.6	589.1	1479.8
Biogas & heat pumps	533.0	119.5	632.9	424.1	1709.5
District heating	525.7	119.1	448.2	1406.1	2499.1
All electric	1052.7	140.4	849.4	0.0	2042.5

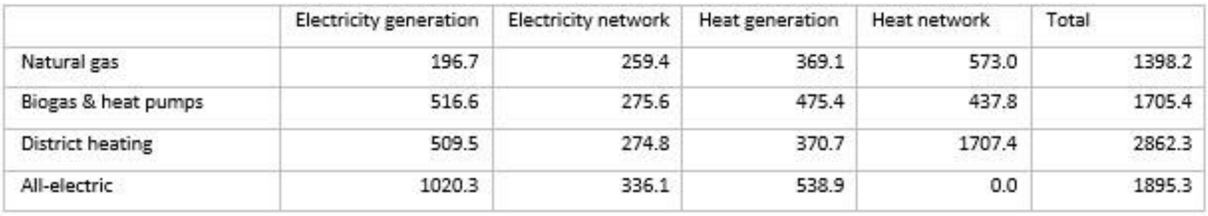
Figure 13 Total materials required per year. Mass adjusted for lifespan of the components.

3.3.1. Embedded climate change impact of materials

The embedded carbon content of the materials displays the same pattern as the material content above. The baseline situation with natural gas heating still has the least carbon content within its materials. The district heating option scores relatively high mostly due to its plastic content.



Climate change impact per subsystem [tonnes CO_2 eq/year]



	Electricity generation	Electricity network	Heat generation	Heat network	Total
Natural gas	196.7	259.4	369.1	573.0	1398.2
Biogas & heat pumps	516.6	275.6	475.4	437.8	1705.4
District heating	509.5	274.8	370.7	1707.4	2862.3
All-electric	1020.3	336.1	538.9	0.0	1895.3

In comparison to the regular embedded carbon content and the adjusted values for the lifespan of the components there is little change in the observed pattern. This can mainly be explained by the similar lifespan of the components within each of the scenarios. Optimisation in terms of prolonging the lifespan of each components therefore not significant when attempting to limit the emissions of the energy infrastructure. In the following subchapter the carbon content of the infrastructure per year will be compared to the emissions during operation.

3.4. Results overview

The materials and their embedded CO_2 impact are lowest in the current natural gas heating scenario. The natural gas scenario serves as a baseline for the current situation. The scenarios which were envisioned for the future have more materials and thereby CO_2 embedded in the infrastructure (Figure 14). The district heating scenario has 68.9% more materials embedded in the energy infrastructure compared to the natural gas scenario. Total embedded impact of the district heating system is 104.7% higher than the natural gas scenario. In case of the all-electric scenario, the score is 38.0% higher for material mass and 35.6% higher for material impact. The combination of biogas and heat pumps scores relatively close to the natural gas scenario with 15.5% and 22.0% higher mass than baseline.

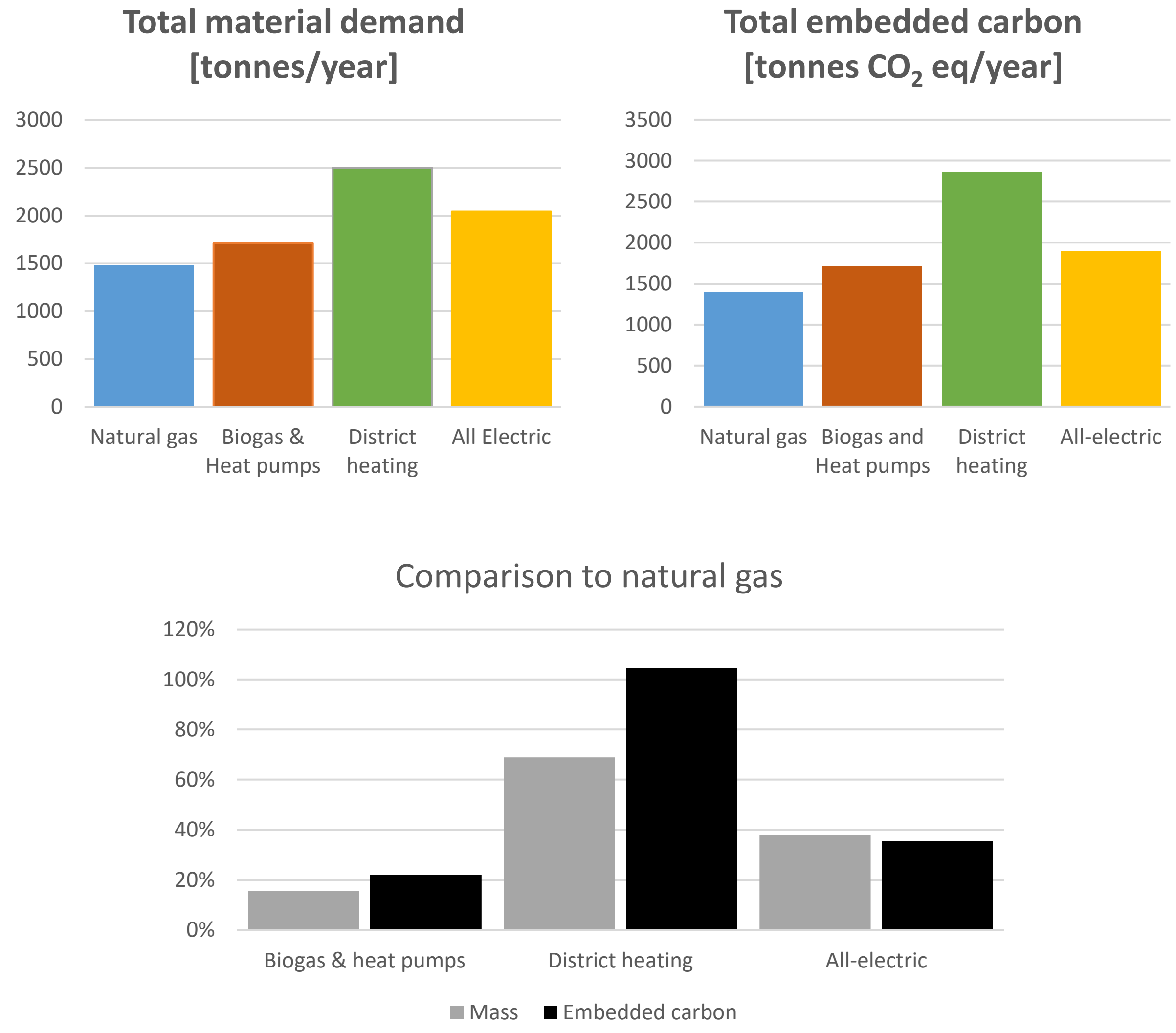
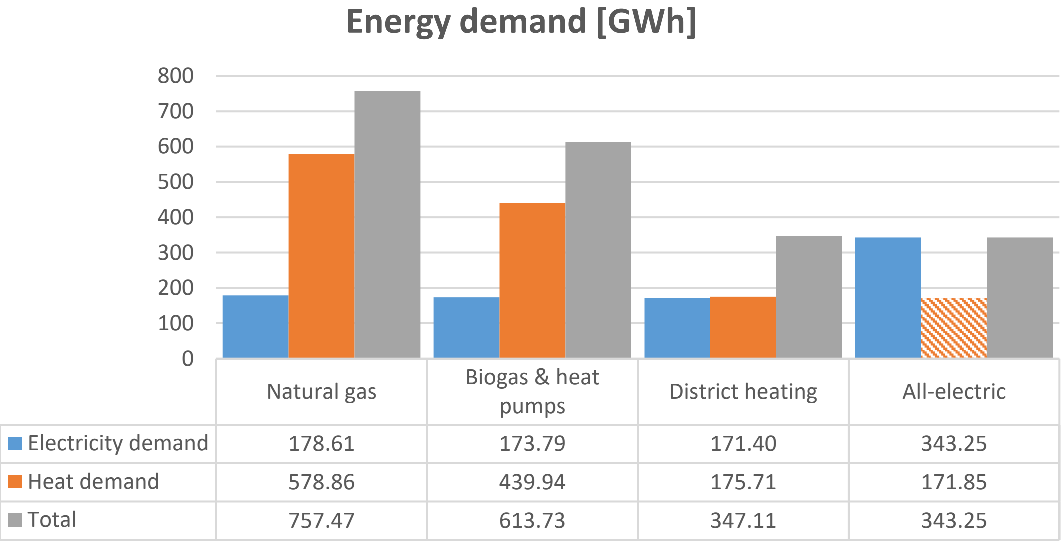


Figure 14 Overview of results. Top left: The total mass required for the energy infrastructure corrected for the lifespan of components. Top right: The total embedded CO_2 of the materials corrected for the lifespan of the components. Bottom mass and embedded carbon content compared to the baseline of natural gas.

Contrarily, the energy demand in future scenarios is considerably lower (Figure 15). The total energy demand of the city dropped by 19.0%, 54.2% and 54.7% for biogas and heat pumps, district heating and all-electric respectively. The fall in energy demand is mainly caused by a reduction in heating demand due to the future scenarios being more efficient. In case of the all-electric scenario, the heating demand is completely satisfied by electricity. In reality, around 50.1% of the electricity demand of the all-electric scenario is used to satisfy the heating of the city. This is indicated by the orange striped area.



	Natural gas	Biogas & heat pumps	District heating	All-electric
🟦 Electricity demand	178.61	173.79	171.40	343.25
🟧 Heat demand	578.86	439.94	175.71	171.85
⬜ Total	757.47	613.73	347.11	343.25

Figure 15: The energy demand of the heating alternatives when applied to Leiden.

The steady drop in energy demand of the heating alternatives raised the question if the embedded carbon content of the energy infrastructure is comparable to the emissions during the use-phase. Table 15 shows an estimation of the use-phase emission based on the heating demand compared to the embedded carbon content. The use-phase emissions of district heating and all-electric scenarios are considerably smaller in relation to the use-phase emissions of the natural gas and biogas scenarios.

Table 15 Emissions during use-phase. The estimated emissions which occur during use-phase of the energy infrastructure. CO_2 emission data per MWh based on (DEFRA, 2007; Middelweerd, 2018; Verhagen, 2018).

	Heating demand per year [GWh/year]	CO_2 per MWh [kg]	Use-phase CO_2 [tonnes/year]	Embedded CO_2 [tonnes/year]	Saved emissions compared to natural gas [tonnes/year]
Natural gas	579	185	$107*10^3$	1398	
Biogas and heat pumps	440	106	$46.8*10^3$	1705	$60.5*10^3$
District Heating	176	107	$18.9*10^3$	2862	$88.3*10^3$
All-electric	172	93	$15.9*10^3$	1895	$91.1*10^3$

4. Conclusion

Deciding which direction to take when changing the heating infrastructure of the Netherlands is a daunting task. There are multiple sustainable alternatives mentioned in governmental policy documents and research papers. Heating by natural gas is deemed unsustainable and therefore changes have to be made. The goal of this thesis was to investigate the influence of the heating transition on energy infrastructure in terms of embedded materials. The heating transition as a whole is a very complex challenge which requires a complex answer. By focussing only on the materials required for the transition one piece of the puzzle might be solved. The goal of the national government and municipality is to reduce the environmental burden of providing energy to cities and as a result battle climate change. The heating techniques and scenarios investigated in this thesis will probably form the basis of the heating transition, but in the future, it is likely that more technological advancements would add to the possible heating alternatives.

The focus of this thesis was on the materials which are embedded in the energy infrastructure and their associated carbon content. However, in the last paragraph of the results section an alarming result was found. The emissions in the use-phase of the heating infrastructure are considerably larger than the carbon content of the materials when these are adjusted for their lifespan (Table 15). In case of an all-electric heating system within the city of Leiden the saved use-phase emissions compared to natural gas are almost 50 times larger than the embedded carbon content. A focus of the municipality on the saved emissions during use-phase would therefore be much more potent in limiting their carbon footprint than focussing on leaner material use.

However, for this thesis the focus was on embedded materials of the energy infrastructure rather than the use-phase emissions. The results indicate that changing our natural gas heating system to a combination of biogas heating and heat pumps results in the least amount of additional materials required. The infrastructural changes required for changing to biogas are minimal as the pipes, pumps and boilers would be totally reusable. The major change which has to occur in this scenario is the construction of large-scale biogas plants. As large petroleum processing facilities are already present in the Rotterdam harbour it might be possible to add biogas processing facilities. However, the major drawback of biogas heating is presented in the literature. The biomass which is required for producing biogas on a similar scale as natural gas is not present in the Netherlands (Connolly et al., 2016, 2014). Therefore, it would be unrealistic to attempt a heating transition to biogas for residential purposes in the Netherlands on a large scale. Nevertheless, biogas could serve a distinct application in old inner cities. Buildings in old inner cities often have the designation of being a "monument" and therefore cannot be visually modified. Adapting these houses to low-temperature heating methods is hardly possible. Therefore, heating these houses with biogas would be the only alternative to natural gas. By strategically planning where to utilise biogas heating, in areas such as old inner cities, would make it possible to use the limited supply of biogas.

Other proposed scenarios require more physical remodelling of energy infrastructure. The district heating alternatives require pipes with more insulation to be installed. The all-electric alternative would require investments, such as the strengthening of low voltage grids, in the electricity network. In-house equipment needs to be changed to either a heat exchanger or heat pump which requires substantially more materials as shown in Figure 9 in the results. The transition to district heating or all-electric will have more impact on residents as the remodelling of pipes and cables which is required is quite substantial. However, in order to limit carbon emissions in the future, such a large systemic change might be required in the end. However, in order to limit the carbon emissions of residential heating in the future significant investments in terms of materials are inevitable. Transitioning to district heating or all-electric requires more materials but is more sustainable in operation.

The proposed system change to district heating for the whole city scores highest of all the alternatives in terms of materials used in the infrastructure as well as the impact of those materials. The additional plastics required for pipe insulation and thicker steel of the pipes are more than double the materials which are required for the heating network in any of the other scenarios. On the other hand, the generation of heat which is required in the heating network is rather lean on materials. This is due to the district heating system being able to utilise residual heat of other industrial processes as a source of energy. Low-temperature district heating could be fuelled by residual heat from datacentres, warehouse cooling or industry with low-quality residual heat. All of these heat sources could be sourced relatively close to the city compared to high-temperature heating sources. The high-temperature alternative would require higher quality heat. In this case, the source would likely be large industrial facilities or power plants which are often further from the city. It remains questionable if enough high-quality heat would be available in the future. Heavy industrial facilities, such as ironworks and oil refineries, are expected to replace carbon-based fuel in their operations. Utilising high-temperature heat would also create a lock-in mechanism where the city would be dependent on the chosen heat source for the coming years. Unfortunate events for such a supplier might therefore turn into a heating crisis for the whole city.

The last alternative is transitioning to a completely electrical heating system. Similar to the district heating alternative the infrastructural changes which are required are substantial. The heating infrastructure of pipes and pumps which is present underground could be removed. This leads to lower maintenance costs of heating infrastructure. At the same time, the electrical household connections which are often a 1x 35A or 40A connections would have to be changed to 3x 25A or 35A. The supporting low-voltage distribution grid requires strengthening too due to an increased electricity demand for electrical heating. The required materials for upgrading the electrical grid as a consequence of electrical heating are only 28% higher than the baseline situation. This mainly leads to more copper and aluminium demand.

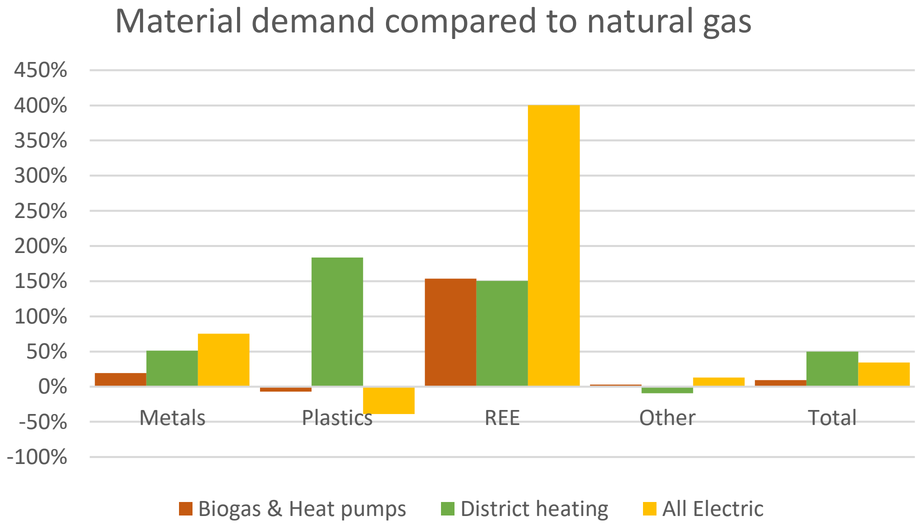


Figure 16 Material demand compared to the materials required for the baseline scenario. The metalloid and non-metals category is left out of the comparison as the percentages were too high compared to the other categories. The scores of this category are BG&HP 790.3%, DH 778.9% and AE 1654.9%.

The demand for rare earth elements would increase considerably due to the heating and energy transition. In this model, the conversion to a more sustainable electricity generation system would mean that demand for rare earth elements such as dysprosium and neodymium would at least double. The metals category also shows a demand increase of between 19.5 and 75.4% (Figure 16). The category of metalloids and non-metals shows an increase of more than 1000% between heating alternatives. This can solely be explained by the silicon which is required for transitioning to power generation by solar PV. The main cause for this phenomenon is the contribution of solar to the total energy grid from 2.5% at baseline to at least 25% in the future.

In the end focussing on the energy infrastructure with the lowest material content would not be the most beneficial method for preventing carbon emissions in the future. The results of this thesis show that the embedded carbon levels of the infrastructure are considerably lower compared to use-phase emissions. The municipality of Leiden should focus on steering the heating transition within the city into the direction of the all-electric scenario. In case of applying the all-electric heating system to Leiden annually the reduction in CO_2 emissions are 91.1 thousand tonnes compared to natural gas (Table 15). But the relatively old inner city would not be able to convert to this low-temperature alternative. The city's building stock is old and fairly poorly insulated, upgrading all of the houses to be suitable for low-temperature heating would be too material intensive. Options to secure high-temperature heat should still be explored in order to supply sufficient heat to the older buildings. Limiting the use of biogas only to the oldest buildings might stretch the supply of biogas enough that sufficient production can be achieved. The emissions which are prevented in case of the combination between biogas and heat pumps are around 60.2 thousand tonnes CO_2 (Table 15). Otherwise a high-temperature district heating connection to the harbour of Rotterdam through the "Warmterontonde" should be explored further. Finally, the heating transition will not be completed anytime soon, but the process of changing neighbourhoods and cities would have to start shortly to achieve the climate change goals set by the government. This paper could be a factor to influence more political steering to certain sustainable heating techniques.

5. Discussion

The results in this paper give an indication that the materials associated with the construction of new energy infrastructure would be considerably larger than the baseline natural gas-based heating system. Components of the natural gas system are relatively simple and mostly rely on materials which are abundantly available such as aluminium, concrete and steel. The other alternatives rely on precious and rare materials to construct a sustainable energy system. Carbon emissions which are embedded in the sustainable heating alternatives are considerably higher than baseline, but this is easily compensated during the use-phase. The use-phase was left out of scope for this thesis, but a simple calculation of the carbon emissions during heat production showed that embedded carbon content is relatively small compared to use-phase carbon emissions. Carbon emissions which are prevented by transitioning away from natural gas are already earned back within the first year of operation. This seems to be rather ambitious but could be explained by embedded emissions only encompassing the materials and not emissions associated with installation and building of the infrastructure.

Similar results were found by van der Kooij (2019). That research investigated the emissions associated with adapting the houses within the "Merenwijk" in Leiden to be converted district heating and all-electric. The results indicated that vast amounts of materials would be required for the adaptation of the houses, but that the impact of the materials would be covered in the first two years of operation. This adds to the conclusion of this report that the materials associated with the construction of energy infrastructure or in-house equipment are significantly smaller than the emissions associated with the use-phase.

Currently, there are more environmental transitions ongoing than just the heating transition. The quest for clean mobility and green electricity are two prominent examples. These transitions require additional critical materials to be mined in the coming years (Bosch, van Exter, Sprecher, de Vries, & Bonenkamp, 2019; van Exter et al., 2018). The critical material demand of the heating transition is slightly smaller compared to the mobility and green electricity transitions as the materials for pipes or boiler/heat pumps are less complex. In case of transitioning to an all-electric heating system, the critical material demand would increase most as the focus would be on solar panels and wind turbines rather than boilers and pipes.

The electricity demand in the all-electric scenario almost doubles compared to baseline. However, the associated grid strengthening and expansion only result in a 20% material demand increase in the electrical network. Decoupling of material and electricity demand is caused by increased heating efficiency of a heat pump compared to a boiler. However, substituting the residential natural gas connection leads to an inevitable further increase in electricity demand due to electrical cooking. On average this would increase the electricity demand by 175 kWh/year/household (Milieu Centraal, n.d.). On a city scale, this could impact the strengthening of the electricity grid further. Gaining more insight into the expected electricity demand of a household if electrification continues is vital for network operators to prepare the grid for the future.

Building age and the choice of heating alternatives are heavily linked as described in the brochure of “Woningwijzerwinkel” (Appendix C) lack of insulation severely limit the application of low-temperature heating. Considering that Leiden has a fairly old building stock, with the average house build in 1929 which is considerably older than the national average of 1962, this might have had an impact on the results of this thesis and whether the results could be extrapolated to the national scale. It would be interesting to investigate the difference in results if the same model would be applied to a major city in which the building stock is younger. It would be expected that low-temperature district heating and all-electric scenarios are more appealing.

In the end, the choice of heating alternative which is most suitable for the city of Leiden will probably not be determined based on the materials which are required for construction of the infrastructure. This thesis was merely an analysis to investigate if the material demand would pose a difficult hurdle. Taking into account carbon emissions which are associated with materials and preventable emissions in the use-phase the three proposed heating scenarios do not differ significantly. Other aspects such as heat source availability, investment cost and social acceptance will be a larger factor for choosing the heating system of the future (CE Delft, 2018; Verhagen, 2018). The Leiden municipality will have to inform its residents of the choices which have to be made to heat the city in a more sustainable fashion. Additionally, they should investigate if reliable sources of residual heat in the proximity of the city can be used in the coming decades. By combining the financial aspect of the transition, preference of citizens and availability of heat sources in the proximity of the city a future vision can be created.

5.1. Limitations and future research

This paper made an attempt by evaluating the materials that would be required for the heating transition in the Netherlands. Most of the material data is based on assumptions and data from diverse sources. This might be one of the biggest limitations as material inventories used in the thesis varied greatly in their reporting style and specificity of reporting. For example, material inventories of solar panel LCA studies mainly report major metals while the use of indium or cadmium was not reported at all. Future research in this area would benefit from unified databases which provide reliable information about materials used for certain products. The information which would be reported in a material passport of a product would be very valuable.

Together with improving the material inventory, the GeoPandas model can be further refined. In this model, the data from governmental sources were combined to gain insight into the energy demand of a building coupled with the building characteristics. The heating demand for houses is reported by the Nationale Energieatlas (CBS, 2014). Information about the building age and dimensions is reported by the BAG (Kadaster, n.d.). Further coupling between heating demand, building age and energy label in one dataset provided by one governmental organisation would give a more accurate estimation of suitable heating techniques and future heating demand. This would lead to a more complete database which could be used by municipalities and network operators to enhance their predictions for the heating transition.

Nation-wide transport of electricity and gas is modelled in this thesis, but it is simplified due to the scope of the study. Modelling the changes which are required on a national scale would result in valuable information for network operators on making the grids future proof with regards to new heating techniques. Network operators possess the information on changes in network loads, but open-source sharing of this information would be useful for future research on this topic. In literature, there is a discussion about smart grids and decentralized heating infrastructure (CE Delft & KEMA, 2012; Naber et al., 2017; R. P. van Leeuwen et al., 2017). Investigating how decentralisation would impact the organisation of the energy infrastructure would be interesting for further expansion of the model presented in this thesis.

Lastly, heating and electricity storage was not included in this paper. It would be interesting to see how the addition of electrical and heating storage would influence the energy infrastructure. Storing of electricity helps with load balancing of the grid and is essential to achieve widespread usage of renewable energy in the electricity mix (Mathiesen et al., 2015). Storage of heat and cold will also be essential to cope with peak heating and cooling loads. Underground storage of heat would be able to flatten the peak loads and allow for smaller heating systems to cope with high demands (Sommer et al., 2014). This would save materials and investments as the dimensions of a heating system would be considerably smaller. Storage of heat and cold underground is already being practically implemented, but material inventories on these storage applications were not available to my knowledge. Additionally, it would be valuable to research how investment in energy storage would influence the energy infrastructure required on a city or national scale. How would energy storage be envisioned on a district or city scale in the future?

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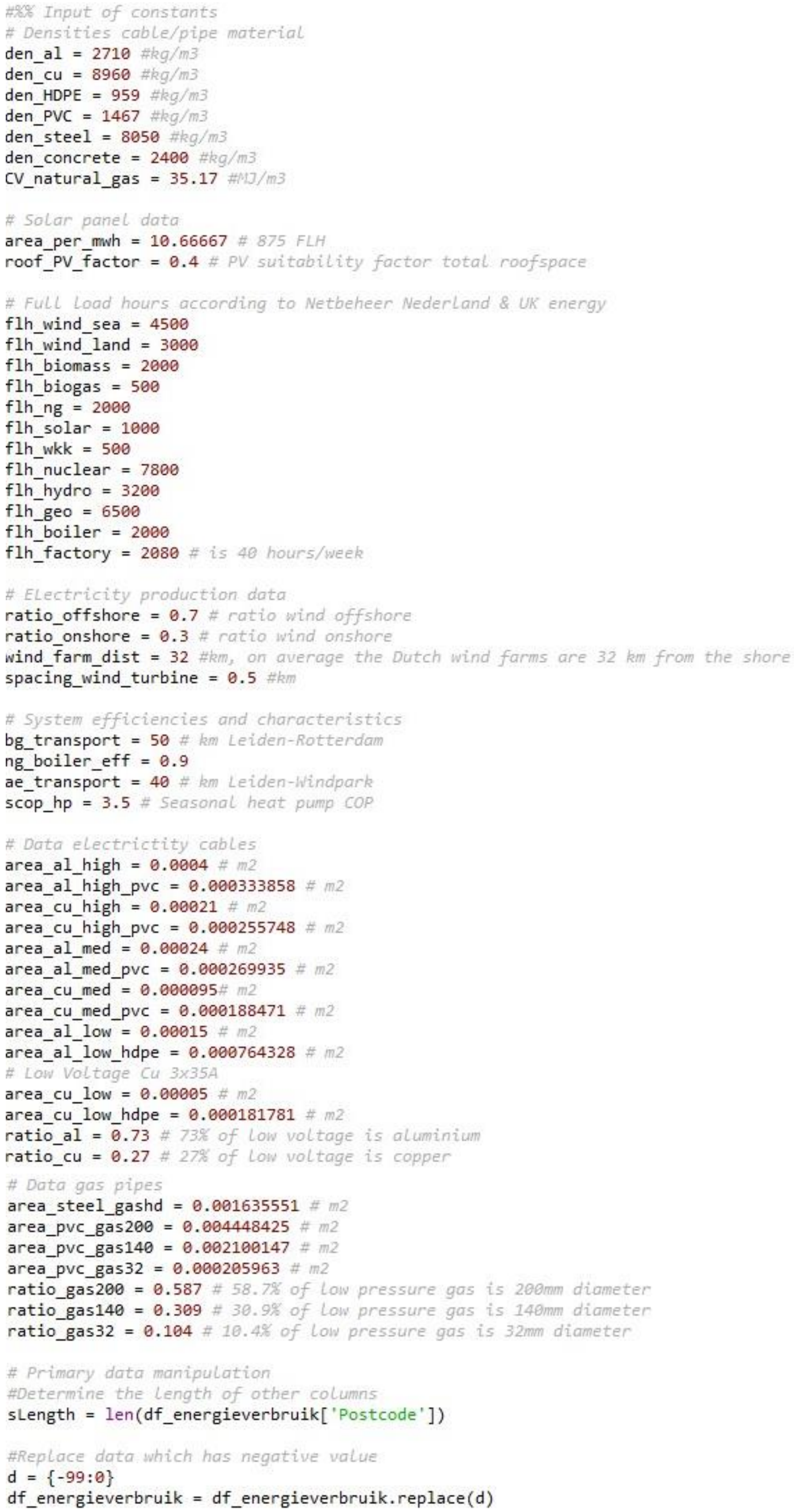
Appendix A: Overview of GeoPandas model

In this appendix the GeoPandas model is explained by showing the code with the corresponding comments. The code shown here is from a scenario with biogas and heat pumps. For each of the scenarios discussed in chapter 3 a Python file similar to this example was created.

The data preparation part of the script. In this part of the code the required Python libraries, datasets and constant are loaded. This part of the code is universal for each of the scenarios.

```
#%%     Import Libaries
import pandas as pd
import geopandas as gpd
import numpy as np
import math
from openpyxl import load_workbook
```

```
#%% Import data
# Leiden geo data
df_borough = gpd.read_file(r'D:\Robert\Studie\Thesis\Thesis_data\Leiden\wijk_Leiden.shp')
cols_to_keep = ['WK_NAAM', 'AANT_INW', 'AANTAL_HH', 'geometry'] # Only keep certain columns
df_borough = df_borough[cols_to_keep]
df_district = gpd.read_file(r'D:\Robert\Studie\Thesis\Thesis_data\Leiden\buurt_Leiden.shp')
cols_to_keep = ['BU_NAAM', 'AANT_INW', 'AANTAL_HH', 'geometry'] # Only keep certain columns
df_district = df_district[cols_to_keep]
df_energieverbruik = gpd.read_file(r'D:\Robert\Studie\Thesis\Thesis_data\Leiden\PC6_woningen_Leiden.shp')
df_bag_leiden = gpd.read_file(r'D:\Robert\Studie\Thesis\Thesis_data\Leiden\BAG_3D_Leiden_woont.shp')

# District heating network Leiden
df_dh_leiden = gpd.read_file(r'D:\Robert\Studie\Thesis\Thesis_data\Leiden\Warmtenet.shp')

# Gas network Leiden
df_gashd_leiden = gpd.read_file(r'D:\Robert\Studie\Thesis\Thesis_data\Leiden\HD_Leiden.shp')
df_gasld_leiden = gpd.read_file(r'D:\Robert\Studie\Thesis\Thesis_data\Leiden\LD_Leiden.shp')

# Electricity network Leiden
df_elec_med_leiden = gpd.read_file(r'D:\Robert\Studie\Thesis\Thesis_data\Leiden\MS_Leiden.shp')
df_elec_high_leiden = gpd.read_file(r'D:\Robert\Studie\Thesis\Thesis_data\Leiden\HS_Leiden.shp')
df_elec_low_leiden = gpd.read_file(r'D:\Robert\Studie\Thesis\Thesis_data\Leiden\LS_Leiden.shp')

# Material data Loading
# Selecting the specific sheet in the excel
df_elec_network = pd.read_excel (r'D:\Robert\Studie\Thesis\Thesis_data\material_data.xlsx',
                                 sheet_name='electrical_network')
df_elec_generator = pd.read_excel (r'D:\Robert\Studie\Thesis\Thesis_data\material_data.xlsx',
                                   sheet_name='electrical_generation')
df_elec_storage = pd.read_excel (r'D:\Robert\Studie\Thesis\Thesis_data\material_data.xlsx',
                                 sheet_name='electrical_storage')
df_heat_network = pd.read_excel (r'D:\Robert\Studie\Thesis\Thesis_data\material_data.xlsx',
                                 sheet_name='heating_network')
df_heat_generator = pd.read_excel (r'D:\Robert\Studie\Thesis\Thesis_data\material_data.xlsx',
                                   sheet_name='heating_generation')
df_inside_house = pd.read_excel (r'D:\Robert\Studie\Thesis\Thesis_data\material_data.xlsx',
                                 sheet_name='inside_house')
material_impact = pd.read_excel (r'D:\Robert\Studie\Thesis\Thesis_data\material_impact.xlsx')
```



```
#%% Input of constants
# Densities cable/pipe material
den_al = 2710 #kg/m3
den_cu = 8960 #kg/m3
den_HDPE = 959 #kg/m3
den_PVC = 1467 #kg/m3
den_steel = 8050 #kg/m3
den_concrete = 2400 #kg/m3
CV_natural_gas = 35.17 #MJ/m3

# Solar panel data
area_per_mwh = 10.66667 # 875 FLH
roof_PV_factor = 0.4 # PV suitability factor total roofspace

# Full load hours according to Netbeheer Nederland & UK energy
flh_wind_sea = 4500
flh_wind_land = 3000
flh_biomass = 2000
flh_biogas = 500
flh_ng = 2000
flh_solar = 1000
flh_wkk = 500
flh_nuclear = 7800
flh_hydro = 3200
flh_geo = 6500
flh_boiler = 2000
flh_factory = 2080 # is 40 hours/week

# Electricity production data
ratio_offshore = 0.7 # ratio wind offshore
ratio_onshore = 0.3 # ratio wind onshore
wind_farm_dist = 32 #km, on average the Dutch wind farms are 32 km from the shore
spacing_wind_turbine = 0.5 #km

# System efficiencies and characteristics
bg_transport = 50 # km Leiden-Rotterdam
ng_boiler_eff = 0.9
ae_transport = 40 # km Leiden-Windpark
scop_hp = 3.5 # Seasonal heat pump COP

# Data electrictity cables
area_al_high = 0.0004 # m2
area_al_high_pvc = 0.000333858 # m2
area_cu_high = 0.00021 # m2
area_cu_high_pvc = 0.000255748 # m2
area_al_med = 0.00024 # m2
area_al_med_pvc = 0.000269935 # m2
area_cu_med = 0.000095# m2
area_cu_med_pvc = 0.000188471 # m2
area_al_low = 0.00015 # m2
area_al_low_hdpe = 0.000764328 # m2
# Low Voltage Cu 3x35A
area_cu_low = 0.00005 # m2
area_cu_low_hdpe = 0.000181781 # m2
ratio_al = 0.73 # 73% of low voltage is aluminium
ratio_cu = 0.27 # 27% of low voltage is copper
# Data gas pipes
area_steel_gashd = 0.001635551 # m2
area_pvc_gas200 = 0.004448425 # m2
area_pvc_gas140 = 0.002100147 # m2
area_pvc_gas32 = 0.000205963 # m2
ratio_gas200 = 0.587 # 58.7% of low pressure gas is 200mm diameter
ratio_gas140 = 0.309 # 30.9% of low pressure gas is 140mm diameter
ratio_gas32 = 0.104 # 10.4% of low pressure gas is 32mm diameter

# Primary data manipulation
#Determine the length of other columns
sLength = len(df_energieverbruik['Postcode'])

#Replace data which has negative value
d = {-99:0}
df_energieverbruik = df_energieverbruik.replace(d)
```

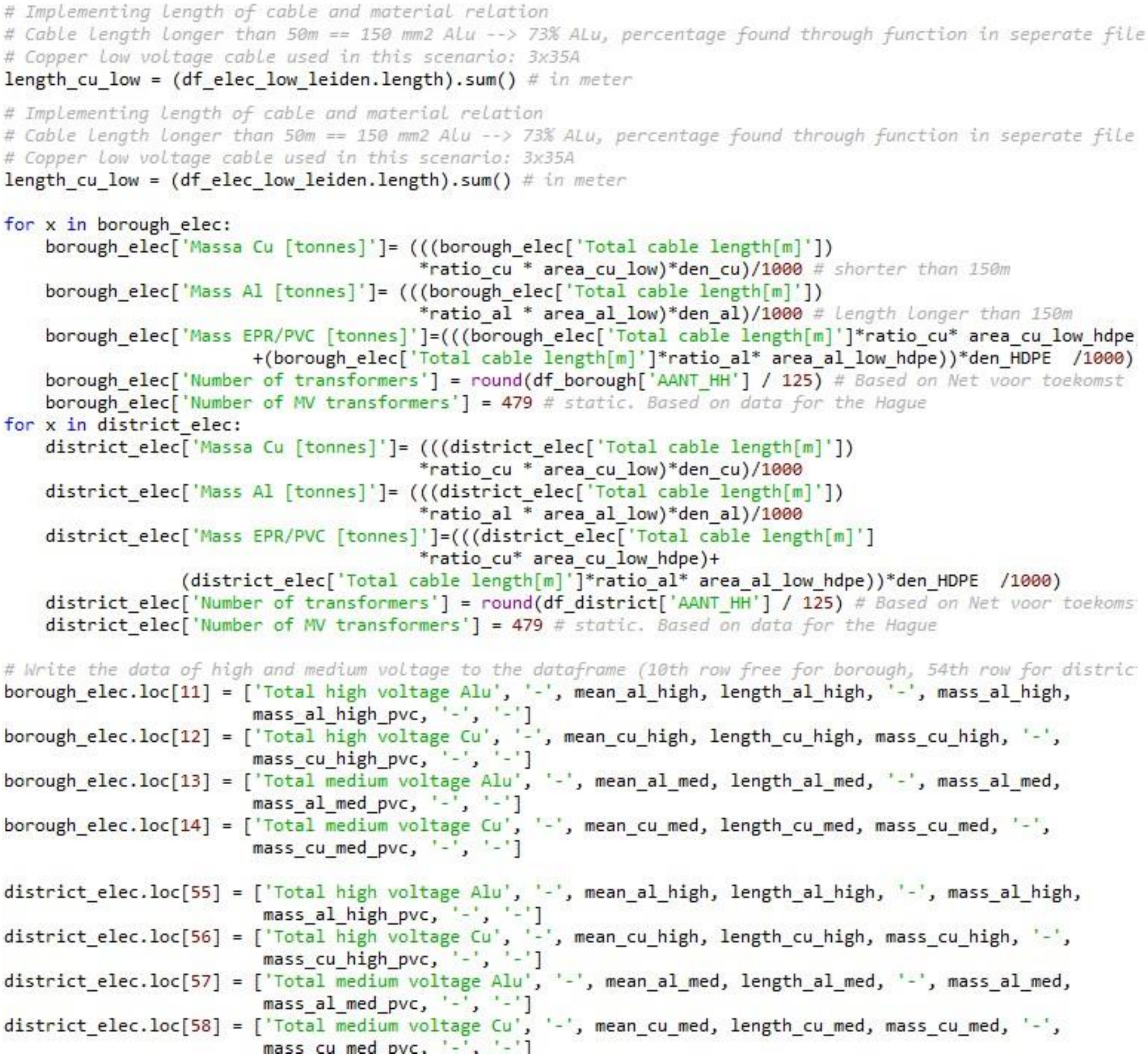
The datasets which were loaded in the previous part are being combined to create datasets which only contain the information which is essential for the research. The datasets are combined through spatial joining with GeoPandas and dissolving the zip code data into the larger boroughs and districts.

```
#%% Prepare data for analysis
# Extract the building age from the BAG_3D datalayer and add to energieverbruik dataframe together
# with total roofarea of buildings
df_bag_leiden = gpd.read_file(r'D:\Robert\Studie\Thesis\Thesis_data\Leiden\BAG_3D_Leiden_woont.shp')
for x in df_bag_leiden:
    df_bag_leiden['Dak oppervlak [m2]'] = df_bag_leiden['geometry'].area # in  m2
cols_to_keep = [ 'Bouwjaar', 'geometry', 'Dak oppervlak [m2]' ] #Extract building age and roof area
df_bag_leiden = df_bag_leiden[cols_to_keep]
df_energieverbruik = gpd.sjoin(df_energieverbruik, df_bag_leiden[['Bouwjaar',
                    'geometry', 'Dak oppervlak [m2]']], how='left', op='intersects') # Join the datasets
df_energieverbruik.dropna(inplace = True)
df_energieverbruik = df_energieverbruik.dissolve(by='Postcode',
                                                 aggfunc = ['mean','sum'], as_index = False)
cols = [3,5,7,9,11,13,14,15,17,18] # remove columns which make no sense
df_energieverbruik.drop(df_energieverbruik.columns[cols], axis=1, inplace=True)
df_energieverbruik.columns= ['Postcode','geometry','G_W_AVG',
                             'G_W_SUM', 'G_W_N', 'E_W_AVG', 'E_W_SUM', 'E_W_N', 'Year_Construction',
                             'Roof Area for PV [m2]'] # Rename
df_energieverbruik.loc[(df_energieverbruik.Year_Construction > 1945) &
                       (df_energieverbruik.Year_Construction <=1974), 'LTH'] = 'HTH with efficiency gain'
df_energieverbruik.loc[(df_energieverbruik.Year_Construction > 1974) &
                       (df_energieverbruik.Year_Construction <=1984), 'LTH'] = 'LTH with efficiency loss'
df_energieverbruik.loc[(df_energieverbruik.Year_Construction > 1984), 'LTH'] = 'Low temperature heating possib
df_energieverbruik.loc[(df_energieverbruik.Year_Construction < 1945), 'LTH'] = 'High temperature heating only'
df_energieverbruik.dropna(inplace = True)

# Create similar databases but split into boroughs
df_borough = gpd.sjoin(df_borough, df_energieverbruik[['geometry', 'G_W_AVG',
    'G_W_SUM', 'G_W_N', 'E_W_AVG', 'E_W_SUM', 'E_W_N', 'Year_Construction', 'Roof Area for PV [m2]']],
    how = 'left', op='intersects')
df_borough.drop('index_right', axis=1, inplace=True)
df_borough = df_borough.dissolve(by='WK_NAAM', aggfunc = ['mean', 'sum'], as_index = False)
cols = [3,5,7,8,10,13,14,16,19,20] #Mean data kept for all but the Sum columns and Roof Area
df_borough.drop(df_borough.columns[cols],axis=1, inplace=True)
df_borough.columns= ['WK_NAAM', 'geometry', 'AANT_INW', 'AANT_HH','G_W_AVG [m3]',
                     'G_W_SUM [m3]', 'G_W_N', 'E_W_AVG [kWh]', 'E_W_SUM [kWh]', 'E_W_N', 'Year_Construction',
                     'Roof Area for PV [m2]']
# Addition of the new borough due to population growth (+7.2%)
# By copying a existing district the geographical data is preserved
options = ['Stevenshofdistrict']
new_district = df_borough[df_borough['WK_NAAM'].isin(options)]
new_district.loc[9, 'WK_NAAM'] = 'New district'
new_district.loc[9, 'G_W_AVG [m3]'] = 932.6 # Add average gas consumption
new_district.loc[9, 'E_W_AVG [kWh]'] = 2497 # Add average electricity consumption
df_borough = df_borough.append(new_district, ignore_index = True)
df_borough = df_borough.sort_values(by=df_borough.columns[0]) # Sort by district name
df_borough = df_borough.reset_index(drop=True) # Apply new index
#Correct the elec and heating demand for future efficiency gain (-25% and -16%)
df_borough['G_W_AVG [m3]'] = df_borough ['G_W_AVG [m3]']*0.84 # Heating demand (-16%)
df_borough['E_W_AVG [kWh]'] = df_borough['E_W_AVG [kWh]']*0.75 # Elec demand (-25%)
for x in df_borough:
    df_borough['Solar Power Capacity [kWh]'] = ((df_borough['Roof Area for PV [m2]']
                                                 *roof_PV_factor)/area_per_mwh)*1000
    df_borough['G_W_SUM [m3]'] = df_borough['AANT_HH'] * df_borough ['G_W_AVG [m3]']
    df_borough['E_W_SUM [kWh]'] = df_borough['AANT_HH'] * df_borough ['E_W_AVG [kWh]']
# Create column which includes low-temperature heating suitability based on year of construction
df_borough.loc[(df_borough.Year_Construction > 1945) & (df_borough.Year_Construction <=1974), 'LTH'] =
                                                                            'HTH with efficiency gain'
df_borough.loc[(df_borough.Year_Construction > 1974) & (df_borough.Year_Construction <=1984), 'LTH'] =
                                                                            'LTH with efficiency loss'
df_borough.loc[(df_borough.Year_Construction > 1984), 'LTH'] = 'Low temperature heating possible'
df_borough.loc[(df_borough.Year_Construction < 1945), 'LTH'] = 'High temperature heating only'

# create similar databases but split into districts
df_district = gpd.sjoin(df_district, df_energieverbruik[['geometry', 'G_W_AVG', 'G_W_SUM',
    'G_W_N', 'E_W_AVG', 'E_W_SUM', 'E_W_N', 'Year_Construction', 'Roof Area for PV [m2]']],
        how = 'left', op='intersects')
df_district.drop('index_right', axis=1, inplace=True)
df_district = df_district.dissolve(by='BU_NAAM', aggfunc = ['mean','sum'], as_index = False)
cols = [3,5,7,8,10,13,14,16,19,20] #Mean data kept for all but the Sum columns and Roof Area
df_district.drop(df_district.columns[cols],axis=1, inplace=True)
df_district.columns= ['BU_NAAM','geometry', 'AANT_INW', 'AANT_HH','G_W_AVG [m3]', 'G_W_SUM [m3]', 'G_W_N',
                      'E_W_AVG [kWh]', 'E_W_SUM [kWh]', 'E_W_N', 'Year_Construction', 'Roof Area for PV [m2]'
```

```
#%% Create Infrastructure databases
# District and gas network combined
# Join the datasets
borough_heat = gpd.sjoin(df_gasld_leiden, df_borough[['geometry', 'WK_NAAM']], how='left', op='within')
# Drop empty lines
borough_heat.dropna()
# Dissolve according to district
borough_heat = borough_heat.dissolve(by='WK_NAAM', aggfunc = ['mean','sum'], as_index = False)
# Select columns which are not required
cols = [2,3,4,5,8,9]
# Drop columns which are not interesting
borough_heat.drop(borough_heat.columns[cols],axis=1, inplace=True)
# Rename for clarity
borough_heat.columns= ['WK_NAAM','geometry', 'Mean pipe length[m]', 'Total pipe length[m]']

# District and electricity network combined
# Join the datasets
borough_elec = gpd.sjoin(df_elec_low_leiden, df_borough[['geometry', 'WK_NAAM']], how='left', op='within')
borough_elec.dropna()
borough_elec = borough_elec.dissolve(by='WK_NAAM', aggfunc = ['mean','sum'], as_index = False)
cols = [2,3,6,7]
borough_elec.drop(borough_elec.columns[cols],axis=1, inplace=True)
borough_elec.columns= ['WK_NAAM','geometry', 'Mean cable length[m]', 'Total cable length[m]']

# Neighbourhood and gas network combined
# Join the datasets
district_heat = gpd.sjoin(df_gasld_leiden, df_district[['geometry', 'BU_NAAM']], how='left', op='within')
district_heat.dropna()
district_heat = district_heat.dissolve(by='BU_NAAM', aggfunc = ['mean','sum'], as_index = False)
cols = [2,3,4,5,8,9]
district_heat.drop(district_heat.columns[cols],axis=1, inplace=True)
district_heat.columns= ['BU_NAAM','geometry', 'Mean pipe length[m]', 'Total pipe length[m]']

# Neighbourhood and electricity network combined
# Join the datasets
district_elec = gpd.sjoin(df_elec_low_leiden, df_district[['geometry', 'BU_NAAM']], how='left', op='within')
district_elec.dropna()
district_elec = district_elec.dissolve(by='BU_NAAM', aggfunc = ['mean','sum'], as_index = False)
cols = [2,3,6,7]
district_elec.drop(district_elec.columns[cols],axis=1, inplace=True)
district_elec.columns= ['BU_NAAM','geometry', 'Mean cable length[m]', 'Total cable length[m]']
```

```
#%% Electricity section
# High and medium voltage are seperate. They intersect too many districts and therefore get counted double
# High voltage
# Aluminium  Conductor cross section 0.0004 m2
df_al_high = df_elec_high_leiden[df_elec_high_leiden['MATERIAAL'].isin(['Al','AL'])]
length_al_high = (df_al_high.length).sum() # in meter
mean_al_high = (df_al_high.length).mean()
mass_al_high = ((length_al_high * area_al_high)*den_al)/1000 # in tonnes
mass_al_high_pvc = ((length_al_high * area_al_high_pvc)*den_PVC)/1000 # in tonnes

# Copper Conductor cross section 0.00021 m2
df_cu_high = df_elec_high_leiden[df_elec_high_leiden['MATERIAAL'].isin(['Cu'])]
length_cu_high = (df_cu_high.length).sum() # in meter
mean_cu_high = (df_cu_high.length).mean()
mass_cu_high = ((length_cu_high * area_cu_high)*den_cu)/1000 # in tonnes
mass_cu_high_pvc = ((length_cu_high * area_cu_high_pvc)*den_PVC)/1000 # in tonnes

# Medium Voltage
# Aluminium Conductor cross section 0.00024 m2
df_al_med = df_elec_med_leiden[df_elec_med_leiden['MATERIAAL'].isin(['Al','Al massief'])]
length_al_med = (df_al_med.length).sum() # in meter
mean_al_med = (df_al_med.length).mean()
mass_al_med = ((length_al_med * area_al_med)*den_al)/1000 # in tonnes
mass_al_med_pvc = ((length_al_med * area_al_med_pvc)*den_PVC)/1000 # in tonnes

# Copper Conductor cross section 0.000095 m2
df_cu_med = df_elec_med_leiden[df_elec_med_leiden['MATERIAAL'].isin(['Cu'])]
length_cu_med = (df_cu_med.length).sum() # in meter
mean_cu_med = (df_cu_med.length).mean()
mass_cu_med = ((length_cu_med * area_cu_med)*den_cu)/1000 # in tonnes
mass_cu_med_pvc = ((length_cu_med * area_cu_med_pvc)*den_PVC)/1000 # in tonnes
```

In this section the materials required for the low voltage electricity network are calculated. In the high and medium voltage network data there was information present on the materials used in the cables. However, this information was lacking in the low voltage dataset. Therefore and assumption was made that cables longer than 50 meters were made from aluminium and the cables shorter than 50 meters were made from copper.



```
# Implementing length of cable and material relation
# Cable length longer than 50m == 150 mm2 Alu --> 73% ALu, percentage found through function in seperate file
# Copper low voltage cable used in this scenario: 3x35A
length_cu_low = (df_elec_low_leiden.length).sum() # in meter

# Implementing length of cable and material relation
# Cable length longer than 50m == 150 mm2 Alu --> 73% ALu, percentage found through function in seperate file
# Copper low voltage cable used in this scenario: 3x35A
length_cu_low = (df_elec_low_leiden.length).sum() # in meter

for x in borough_elec:
    borough_elec['Massa Cu [tonnes]']= (((borough_elec['Total cable length[m]'])
                                        *ratio_cu * area_cu_low)*den_cu)/1000 # shorter than 150m
    borough_elec['Mass Al [tonnes]']= (((borough_elec['Total cable length[m]'])
                                        *ratio_al * area_al_low)*den_al)/1000 # length longer than 150m
    borough_elec['Mass EPR/PVC [tonnes]']=(((borough_elec['Total cable length[m]']*ratio_cu* area_cu_low_hdpe
                        +(borough_elec['Total cable length[m]']*ratio_al* area_al_low_hdpe))*den_HDPE  /1000)
    borough_elec['Number of transformers'] = round(df_borough['AANT_HH'] / 125) # Based on Net voor toekomst
    borough_elec['Number of MV transformers'] = 479 # static. Based on data for the Hague
for x in district_elec:
    district_elec['Massa Cu [tonnes]']= (((district_elec['Total cable length[m]'])
                                        *ratio_cu * area_cu_low)*den_cu)/1000
    district_elec['Mass Al [tonnes]']= (((district_elec['Total cable length[m]'])
                                        *ratio_al * area_al_low)*den_al)/1000
    district_elec['Mass EPR/PVC [tonnes]']=(((district_elec['Total cable length[m]']
                                        *ratio_cu* area_cu_low_hdpe)+
                 (district_elec['Total cable length[m]']*ratio_al* area_al_low_hdpe))*den_HDPE  /1000)
    district_elec['Number of transformers'] = round(df_district['AANT_HH'] / 125) # Based on Net voor toekoms
    district_elec['Number of MV transformers'] = 479 # static. Based on data for the Hague

# Write the data of high and medium voltage to the dataframe (10th row free for borough, 54th row for distric
borough_elec.loc[11] = ['Total high voltage Alu', '-', mean_al_high, length_al_high, '-', mass_al_high,
                        mass_al_high_pvc, '-', '-']
borough_elec.loc[12] = ['Total high voltage Cu', '-', mean_cu_high, length_cu_high, mass_cu_high, '-',
                        mass_cu_high_pvc, '-', '-']
borough_elec.loc[13] = ['Total medium voltage Alu', '-', mean_al_med, length_al_med, '-', mass_al_med,
                        mass_al_med_pvc, '-', '-']
borough_elec.loc[14] = ['Total medium voltage Cu', '-', mean_cu_med, length_cu_med, mass_cu_med, '-',
                        mass_cu_med_pvc, '-', '-']

district_elec.loc[55] = ['Total high voltage Alu', '-', mean_al_high, length_al_high, '-', mass_al_high,
                         mass_al_high_pvc, '-', '-']
district_elec.loc[56] = ['Total high voltage Cu', '-', mean_cu_high, length_cu_high, mass_cu_high, '-',
                         mass_cu_high_pvc, '-', '-']
district_elec.loc[57] = ['Total medium voltage Alu', '-', mean_al_med, length_al_med, '-', mass_al_med,
                         mass_al_med_pvc, '-', '-']
district_elec.loc[58] = ['Total medium voltage Cu', '-', mean_cu_med, length_cu_med, mass_cu_med, '-',
                         mass cu med pvc, '-', '-']
```

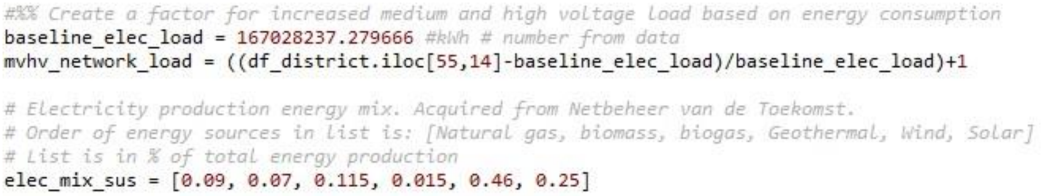
```
#%% Biogas section
# Add columns which will be filled
borough_heat['Massa PVC/PE [tonnes]'] = '-'
borough_heat['Mass steel [tonnes]'] = '-'
district_heat['Massa PVC/PE [tonnes]'] = '-'
district_heat['Mass steel [tonnes]'] = '-'

# Add LTH type for further processing
borough_heat['LTH'] = df_borough['LTH']
district_heat['LTH'] = df_district['LTH']

# Modification of heat infrastructure. Natural gas pipes removed in districts capable of LTH
# House type 1:
borough_heat.loc[borough_heat['LTH'] == 'High temperature heating only', 'Total pipe length[m]'] =
                                                                      borough_heat['Total pipe length[m]']
district_heat.loc[district_heat['LTH'] == 'High temperature heating only', 'Total pipe length[m]'] =
                                                                      district_heat['Total pipe length[m]']
# House type 2:
borough_heat.loc[borough_heat['LTH'] == 'HTH with efficiency gain', 'Total pipe length[m]'] =
                                                                      borough_heat['Total pipe length[m]']
district_heat.loc[district_heat['LTH'] == 'HTH with efficiency gain', 'Total pipe length[m]'] =
                                                                      district_heat['Total pipe length[m]']
# House type 3:
borough_heat.loc[borough_heat['LTH'] == 'LTH with efficiency loss', 'Total pipe length[m]'] =
                                                                      borough_heat['Total pipe length[m]']*0
district_heat.loc[district_heat['LTH'] == 'LTH with efficiency loss', 'Total pipe length[m]'] =
                                                                      district_heat['Total pipe length[m]']*0
# House type 4:
borough_heat.loc[borough_heat['LTH'] == 'Low temperature heating possible', 'Total pipe length[m]'] =
                                                                      borough_heat['Total pipe length[m]']*0
district_heat.loc[district_heat['LTH'] == 'Low temperature heating possible', 'Total pipe length[m]'] =
                                                                      district_heat['Total pipe length[m]']*0
# Gas pipes
# High pressure --> mostly diamter 300 mm, See appendix tables for dimensions
length_gashd = (df_gashd_leiden.length).sum()
mean_gashd = (df_gashd_leiden.length).mean()
mass_highp_gas_steel = ((length_gashd *area_steel_gashd)*den_steel)/1000 # in tonnes

# Mass of pipes
length_gasld = (df_gasld_leiden.length).sum()
for x in borough_heat:
    borough_heat['Massa PVC/PE [tonnes]']= ((((borough_heat['Total pipe length[m]']
                *ratio_gas200)*area_pvc_gas200)+
                ((borough_heat['Total pipe length[m]']*ratio_gas140)*area_pvc_gas140)+
                ((borough_heat['Total pipe length[m]']*ratio_gas32)*area_pvc_gas32))*den_PVC)/1000
    borough_heat['Mass steel [tonnes]'] = '-' # Add column for new data
for x in district_heat:
    district_heat['Massa PVC/PE [tonnes]']= ((((district_heat['Total pipe length[m]']
                *ratio_gas200)*area_pvc_gas200)+
                 ((district_heat['Total pipe length[m]']*ratio_gas140)*area_pvc_gas140)+
                 ((district_heat['Total pipe length[m]']*ratio_gas32)*area_pvc_gas32))*den_PVC)/1000
    district_heat['Mass steel [tonnes]'] = '-' # Add column for new data

#Existing District Heating removed, because of overlap
borough_heat.loc[11] = ['Total high pressure gas 150mm', '-', mean_gashd, length_gashd, '-' ,
                        mass_highp_gas_steel, '-']
district_heat.loc[55] = ['Total high pressure gas 150mm', '-', mean_gashd, length_gashd,'-' ,
                        mass_highp_gas_steel, '-']

# Write data to excel
writer = pd.ExcelWriter(r'C:\Users\Robert\Documents\Industrial Ecology\Jaar 2\Thesis\Python\Results\
                Comparison\Leiden-The Hague\Leiden_Infra_Biogas_Heat_Pumps.xlsx', engine= 'xlsxwriter')
borough_elec.to_excel(writer, sheet_name='borough elec infra')
district_elec.to_excel(writer, sheet_name='district elec infra')
borough_heat.to_excel(writer, sheet_name='borough gas infra')
district_heat.to_excel(writer, sheet_name='district gas infra')
writer.save()
```

The dataset which was used for the energy demand contained the gas consumption in cubic meters and this had to be converted to kWh. An assumed efficiency of 90% for boilers was taken into account the primary energy which would be required for heating of the houses. For the houses which would be heated by heat pumps the heating demand would be divided by the SCOP of the boiler and added to the electricity demand. This would emulate the conversion to electrified heating.

```
#%%    Conversion gas to kWh
# Remeber G_W_SUM is in m3 and E_W_SUM is in kWh and ..._N is amount of adresses
# Applied factor 0.9 for efficiency of boilers and 1 kWh = 3.6 MJ
# Efficiency of boiler (90%) required due to old data all heat produced by boilers
df_borough['G_W_SUM [m3]'] = ((df_borough['G_W_SUM [m3]'] * CV_natural_gas)/3.6)*ng_boiler_eff
df_borough['G_W_AVG [m3]'] = ((df_borough['G_W_AVG [m3]'] * CV_natural_gas)/3.6)*ng_boiler_eff
df_borough.rename(columns={'G_W_SUM [m3]':'G_W_SUM [kWh]'}, inplace=True)
df_borough.rename(columns={'G_W_AVG [m3]':'G_W_AVG [kWh]'}, inplace=True)

df_district['G_W_SUM [m3]'] = ((df_district['G_W_SUM [m3]'] * CV_natural_gas)/3.6)*ng_boiler_eff
df_district['G_W_AVG [m3]'] = ((df_district['G_W_AVG [m3]'] * CV_natural_gas)/3.6)*ng_boiler_eff
df_district.rename(columns={'G_W_SUM [m3]':'G_W_SUM [kWh]'}, inplace=True)
df_district.rename(columns={'G_W_AVG [m3]':'G_W_AVG [kWh]'}, inplace=True)

# Modification of elec and heat demand. Heating system efficiencies added for the specific household type.
# House type 3 & 4 convert the heat demand to electricity demand through heat pumps
# House type 1:
df_borough.loc[df_borough['LTH'] == 'High temperature heating only', 'E+W_SUM [kWh]'] =
                                                                     df_borough['E_W_SUM [kWh]']
df_district.loc[df_district['LTH'] == 'High temperature heating only', 'E+W_SUM [kWh]'] =
                                                                     df_district['E_W_SUM [kWh]']
df_borough.loc[df_borough['LTH'] == 'High temperature heating only', 'G_W_SUM [kWh]'] =
                                                                     df_borough['G_W_SUM [kWh]']/(ng_boiler_eff)
df_district.loc[df_district['LTH'] == 'High temperature heating only', 'G_W_SUM [kWh]'] =
                                                                     df_district['G_W_SUM [kWh]']/(ng_boiler_eff)
# House type 2:
df_borough.loc[df_borough['LTH'] == 'HTH with efficiency gain', 'E+W_SUM [kWh]'] =
                                                                     df_borough['E_W_SUM [kWh]']
df_district.loc[df_district['LTH'] == 'HTH with efficiency gain', 'E+W_SUM [kWh]'] =
                                                                     df_district['E_W_SUM [kWh]']
df_borough.loc[df_borough['LTH'] == 'HTH with efficiency gain', 'G_W_SUM [kWh]'] =
                                                                     df_borough['G_W_SUM [kWh]']/(ng_boiler_eff)
df_district.loc[df_district['LTH'] == 'HTH with efficiency gain', 'G_W_SUM [kWh]'] =
                                                                     df_district['G_W_SUM [kWh]']/(ng_boiler_eff)
# House type 3:
df_borough.loc[df_borough['LTH'] == 'LTH with efficiency loss', 'E+W_SUM [kWh]'] =
                                           ((df_borough['G_W_SUM [kWh]'] / scop_hp)+df_borough['E_W_SUM [kWh]'])
df_district.loc[df_district['LTH'] == 'LTH with efficiency loss', 'E+W_SUM [kWh]'] =
                                           ((df_district['G_W_SUM [kWh]'] /scop_hp)+df_district['E_W_SUM [kWh]']
df_borough.loc[df_borough['LTH'] == 'LTH with efficiency loss', 'G_W_SUM [kWh]'] =
                                           df_borough['G_W_SUM [kWh]']*0
df_district.loc[df_district['LTH'] == 'LTH with efficiency loss', 'G_W_SUM [kWh]'] =
                                           df_district['G_W_SUM [kWh]']*0
# House type 4:
df_borough.loc[df_borough['LTH'] == 'Low temperature heating possible', 'E+W_SUM [kWh]'] =
                                           ((df_borough['G_W_SUM [kWh]'] / scop_hp)+df_borough['E_W_SUM [kWh]'])
df_district.loc[df_district['LTH'] == 'Low temperature heating possible', 'E+W_SUM [kWh]'] =
                                           ((df_district['G_W_SUM [kWh]'] / scop_hp)+df_district['E_W_SUM [kWh]'
df_borough.loc[df_borough['LTH'] == 'Low temperature heating possible', 'G_W_SUM [kWh]'] =
                                           df_borough['G_W_SUM [kWh]']*0
df_district.loc[df_district['LTH'] == 'Low temperature heating possible', 'G_W_SUM [kWh]'] =
                                           df_district['G_W_SUM [kWh]']*0
```

```
# Summing heating demand for neighbourhoods which can be converted to LTH
options = ['LTH with efficiency loss', 'Low temperature heating possible']
heat_demand_lth = df_district[df_district['LTH'].isin(options)]
heat_demand_lth_sum = heat_demand_lth['G_W_SUM [kWh]'].sum()

# Summing heating demand for neighbourhoods which cannot be converted to LTH
options = ['High temperature heating only', 'HTH with efficiency gain']
heat_demand_hth = df_district[df_district['LTH'].isin(options)]
heat_demand_hth_sum = heat_demand_hth['G_W_SUM [kWh]'].sum()

# Summing the households which can be converted to LTH
options = ['LTH with efficiency loss', 'Low temperature heating possible']
households_lth = df_district[df_district['LTH'].isin(options)]
households_lth_sum = heat_demand_lth['AANT_HH'].sum()

# Summing the households which cannot be converted to LTH
options = ['High temperature heating only', 'HTH with efficiency gain']
households_hth = df_district[df_district['LTH'].isin(options)]
households_hth_sum = heat_demand_hth['AANT_HH'].sum()

# Creating heating mix based on the type of heating demand in district[ LTH, HTH ]
heat_demand_total = df_district['G_W_SUM [kWh]'].sum()
heat_mix = [(heat_demand_lth_sum/heat_demand_total),(heat_demand_hth_sum/heat_demand_total) ]

# Add line with totals
df_borough.loc[11] = ['Total Leiden', '-',df_borough['AANT_INW'].sum(),df_borough['AANT_HH'].sum(),
          df_borough['G_W_AVG [kWh]'].mean(), df_borough['G_W_SUM [kWh]'].sum(), df_borough['G_W_N'].sum(),
          df_borough['E_W_AVG [kWh]'].mean(), df_borough['E_W_SUM [kWh]'].sum(), df_borough['E_W_N'].sum(),
          df_borough['Year_Construction'].mean(), df_borough['Roof Area for PV [m2]'].sum(),
          df_borough['Solar Power Capacity [kWh]'].sum(), '-', df_borough['E+W_SUM [kWh]'].sum()]
# Add line with totals
df_district.loc[55] = ['Total Leiden', '-',df_district['AANT_INW'].sum(),df_district['AANT_HH'].sum(),
         df_district['G_W_AVG [kWh]'].mean(), df_district['G_W_SUM [kWh]'].sum(), df_district['G_W_N'].sum(),
         df_district['E_W_AVG [kWh]'].mean(), df_district['E_W_SUM [kWh]'].sum(), df_district['E_W_N'].sum(),
         df_district['Year_Construction'].mean(), df_district['Roof Area for PV [m2]'].sum(),
         df_district['Solar Power Capacity [kWh]'].sum(), '-',df_district['E+W_SUM [kWh]'].sum()]

# Write data to excel
writer = pd.ExcelWriter(r'C:\Users\Robert\Documents\Industrial Ecology\Jaar 2\Thesis\Python\Results\
                Comparison\Leiden-The Hague\Leiden_Consumption_Biogas_Heat_Pumps.xlsx', engine= 'xlsxwriter')
df_borough.to_excel(writer, sheet_name='Borough Consumption')
df_district.to_excel(writer, sheet_name='District Consumption')
writer.save()


# Export borough and district data to shapefile to create maps
df_borough.drop(11, inplace=True)
df_district.drop(55, inplace=True)

df_borough.crs = ("+proj=sterea +lat_0=52.15616055555555 +lon_0=5.38763888888889 +k=0.9999079 +x_0=155000 \
                  +y_0=463000 +ellps=bessel +units=m +no_defs")
df_district.crs = ("+proj=sterea +lat_0=52.15616055555555 +lon_0=5.38763888888889 +k=0.9999079 +x_0=155000 \
                   +y_0=463000 +ellps=bessel +units=m +no_defs")

output_maps = r"C:\Users\Robert\Documents\Industrial Ecology\Jaar 2\Thesis\Python\Results\Maps\borough_maps.shp"
df_borough = gpd.GeoDataFrame(df_borough, geometry='geometry', )
df_borough.to_file(output_maps, driver='ESRI Shapefile')
df_district = gpd.GeoDataFrame(df_district, geometry='geometry')
output_maps = r"C:\Users\Robert\Documents\Industrial Ecology\Jaar 2\Thesis\Python\Results\Maps\district_maps.shp"
df_district.to_file(output_maps, driver='ESRI Shapefile')
```

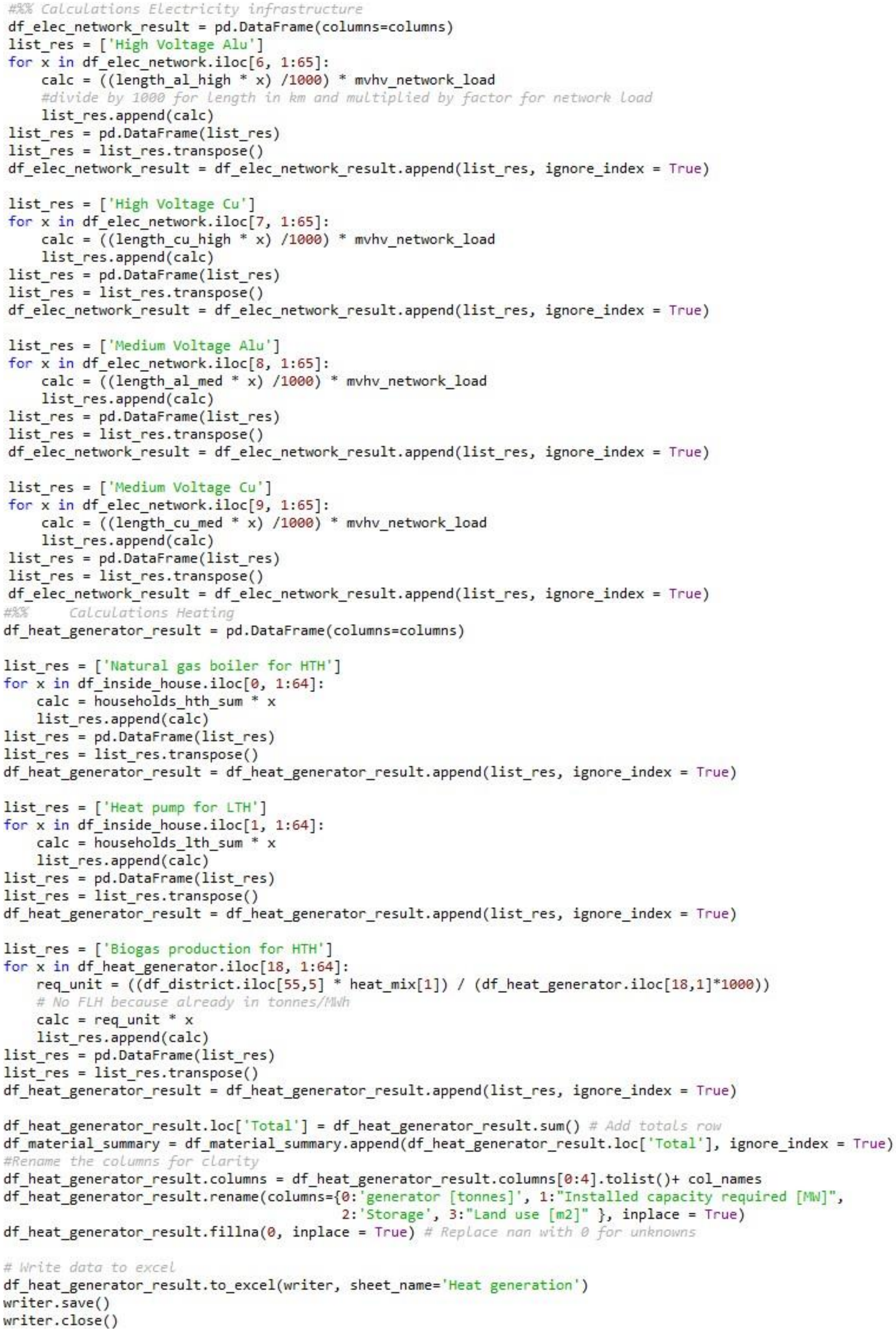
In order to compare the network load of the medium and high voltage networks a comparison was made with the baseline situation. The electricity demand of the chosen scenario would be compared to the baseline situation to estimate the required upgrading of the electricity transport grids.



```
#%% Create a factor for increased medium and high voltage load based on energy consumption
baseline_elec_load = 167028237.279666 #kWh # number from data
mvhv_network_load = ((df_district.iloc[55,14]-baseline_elec_load)/baseline_elec_load)+1

# Electricity production energy mix. Acquired from Netbeheer van de Toekomst.
# Order of energy sources in list is: [Natural gas, biomass, biogas, Geothermal, Wind, Solar]
# List is in % of total energy production
elec_mix_sus = [0.09, 0.07, 0.115, 0.015, 0.46, 0.25]
```

Here the calculation section starts which was used to determine the required material for each part of the energy infrastructure. In this example only the electricity production, network and heat network sections are shown to decrease the size of the appendix. For each section of the energy infrastructure the required power is compared to the database with materials for each infrastructure component. The results are added to a dataset which provides the main results of the analysis.

```
#%% Calculating the results
# Extract the column names for later processing
col_names = list(df_elec_generator)
del(col_names[0:4])

# Create summary dataframe
index = range(5)
columns = range(64)
df_material_summary = pd.DataFrame(columns=columns)
#%%     Calculations Electricity
df_elec_generator_result = pd.DataFrame(columns=columns) # Create the results dataframe
# comments describe first calculation as example. Everything hereafter follows this example.
list_res = ['Natural gas PP']
for x in df_elec_generator.iloc[12, 1:65]: # Select specific datarow for natural gas PP
    req_unit = ((df_district.iloc[55,14]*elec_mix_sus[0])/
                (df_elec_generator.iloc[12,1]*1000*flh_ng))
    # (total elec demand*ratio NG)/(power capacity NG [MW] * 1000 (for kW) * full load hours of NG PP)
    calc = req_unit * x # Calculate the required installed capacity of NG PP
    list_res.append(calc) # Apppend materials to new list
list_res = pd.DataFrame(list_res) # Create dataframe from list
list_res = list_res.transpose() # Transpose data
# Add to results dataframe
df_elec_generator_result = df_elec_generator_result.append(list_res, ignore_index = True)

list_res = ['Wind Offshore'] # 70% of wind is offshore
for x in df_elec_generator.iloc[9, 1:65]:
    req_unit = ((df_district.iloc[55,14]*elec_mix_sus[4]*ratio_offshore) /
                (df_elec_generator.iloc[9,1]*1000*flh_wind_sea))
    calc = req_unit * x
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_elec_generator_result = df_elec_generator_result.append(list_res, ignore_index = True)

list_res = ['Wind Onshore']# uses the average onshore turbine
for x in df_elec_generator.iloc[16, 1:65]: # 30% of wind is onshore
    req_unit = ((df_district.iloc[55,14]*elec_mix_sus[4]*ratio_onshore) /
                (df_elec_generator.iloc[16,1]*1000*flh_wind_land))
    calc = req_unit * x
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_elec_generator_result = df_elec_generator_result.append(list_res, ignore_index = True)

# Add totals row
df_elec_generator_result.loc['Total'] = df_elec_generator_result.sum()
df_material_summary = df_material_summary.append(df_elec_generator_result.loc['Total'], ignore_index = True)

#Rename the columns for clarity
df_elec_generator_result.columns = df_elec_generator_result.columns[0:4].tolist()+ col_names
df_elec_generator_result.rename(columns={0:'Generator [tonnes]', 1:"Installed capacity required [MW]",
                                        2:'Storage', 3:"Land use [m2]" }, inplace = True)
df_elec_generator_result.fillna(0, inplace = True) # Replace nan with 0 for unknowns

# Write data to excel
path = r'C:\Users\Robert\Documents\Industrial Ecology\Jaar 2\Thesis\Python\Results\
          Comparison\Leiden-The Hague\Leiden_Materials_Biogas_Heat_Pumps.xlsx'
writer = pd.ExcelWriter(path, engine= 'openpyxl')
df_elec_generator_result.to_excel(writer, sheet_name='Elec generation')
writer.save()
writer.close()
```



```
#%% Calculations Electricity infrastructure
df_elec_network_result = pd.DataFrame(columns=columns)
list_res = ['High Voltage Alu']
for x in df_elec_network.iloc[6, 1:65]:
    calc = ((length_al_high * x) /1000) * mvhv_network_load
    #divide by 1000 for length in km and multiplied by factor for network load
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_elec_network_result = df_elec_network_result.append(list_res, ignore_index = True)

list_res = ['High Voltage Cu']
for x in df_elec_network.iloc[7, 1:65]:
    calc = ((length_cu_high * x) /1000) * mvhv_network_load
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_elec_network_result = df_elec_network_result.append(list_res, ignore_index = True)

list_res = ['Medium Voltage Alu']
for x in df_elec_network.iloc[8, 1:65]:
    calc = ((length_al_med * x) /1000) * mvhv_network_load
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_elec_network_result = df_elec_network_result.append(list_res, ignore_index = True)

list_res = ['Medium Voltage Cu']
for x in df_elec_network.iloc[9, 1:65]:
    calc = ((length_cu_med * x) /1000) * mvhv_network_load
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_elec_network_result = df_elec_network_result.append(list_res, ignore_index = True)
#%%    Calculations Heating
df_heat_generator_result = pd.DataFrame(columns=columns)

list_res = ['Natural gas boiler for HTH']
for x in df_inside_house.iloc[0, 1:64]:
    calc = households_hth_sum * x
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_heat_generator_result = df_heat_generator_result.append(list_res, ignore_index = True)

list_res = ['Heat pump for LTH']
for x in df_inside_house.iloc[1, 1:64]:
    calc = households_lth_sum * x
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_heat_generator_result = df_heat_generator_result.append(list_res, ignore_index = True)

list_res = ['Biogas production for HTH']
for x in df_heat_generator.iloc[18, 1:64]:
    req_unit = ((df_district.iloc[55,5] * heat_mix[1]) / (df_heat_generator.iloc[18,1]*1000))
    # No FLH because already in tonnes/MWh
    calc = req_unit * x
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_heat_generator_result = df_heat_generator_result.append(list_res, ignore_index = True)

df_heat_generator_result.loc['Total'] = df_heat_generator_result.sum() # Add totals row
df_material_summary = df_material_summary.append(df_heat_generator_result.loc['Total'], ignore_index = True)
#Rename the columns for clarity
df_heat_generator_result.columns = df_heat_generator_result.columns[0:4].tolist()+ col_names
df_heat_generator_result.rename(columns={0:'generator [tonnes]', 1:"Installed capacity required [MW]",
                                         2:'Storage', 3:"Land use [m2]" }, inplace = True)
df_heat_generator_result.fillna(0, inplace = True) # Replace nan with 0 for unknowns

# Write data to excel
df_heat_generator_result.to_excel(writer, sheet_name='Heat generation')
writer.save()
writer.close()
```

```python
#%% Heat Infra
df_heat_network_result = pd.DataFrame(columns=columns)
list_res = ['Biogas HTL pipe 400mm']
for x in df_heat_network.iloc[15, 1:64]:
    calc = bg_transport * x # in km
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_heat_network_result = df_heat_network_result.append(list_res, ignore_index = True)

list_res = ['Gas 200mm']
for x in df_heat_network.iloc[3, 1:65]:
    calc = ((length_gasld*ratio_gas200)+length_gashd) * x /1000
    # factor 0.131 according to prevalence in baseline of pipe type
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_heat_network_result = df_heat_network_result.append(list_res, ignore_index = True)

list_res = ['Gas 140mm']
for x in df_heat_network.iloc[4, 1:65]:
    calc = (length_gasld*ratio_gas140) * x /1000
    # factor 0.441 according to prevalence in baseline of pipe type
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_heat_network_result = df_heat_network_result.append(list_res, ignore_index = True)

list_res = ['Gas 32mm']
for x in df_heat_network.iloc[5, 1:65]:
    calc = (length_gasld*ratio_gas32) * x /1000
    # factor 0.428 according to prevalence in baseline of pipe type
    list_res.append(calc)
list_res = pd.DataFrame(list_res)
list_res = list_res.transpose()
df_heat_network_result = df_heat_network_result.append(list_res, ignore_index = True)

df_heat_network_result.loc['Total'] = df_heat_network_result.sum() # Add totals row
df_material_summary = df_material_summary.append(df_heat_network_result.loc['Total'], ignore_index = True)
#Rename the columns for clarity
df_heat_network_result.columns = df_heat_network_result.columns[0:4].tolist()+ col_names
df_heat_network_result.rename(columns={0:'Pipe [tonnes]', 1:"Installed length [km]", 2:'Storage',
                                       3:"Land use [m2]" }, inplace = True)
df_heat_network_result.fillna(0, inplace = True) # Replace nan with 0 for unknowns

# Write data to excel
df_heat_network_result.to_excel(writer, sheet_name='Heat network')
writer.save()
writer.close()
#%% Add the summary dataframe to the excel sheet
df_material_summary.columns = df_material_summary.columns[0:4].tolist()+ col_names
df_material_summary.rename(columns={0:'Type [tonnes]', 1:"Installed capacity [MW] or km", 2:'Storage [MWh]',
                                    3:"land use [m2]" }, inplace = True)
df_material_summary.fillna(0, inplace = True) # Replace nan with 0 for unknowns
df_material_summary = df_material_summary.rename(index={0:'Elec generator', 1:'Elec network',
                                                        2:'Heat generator', 3: 'Heat network'})
df_material_summary.loc['Total'] = df_material_summary.sum() # Add totals row

# Write summary to Excel
book = load_workbook(path)
writer.book = book
df_material_summary.to_excel(writer, sheet_name='Summary')
writer.save()
writer.close()
```

The final part of the Python script is the comparison between the required materials for each infrastructure subsystem and the associated impact of the materials involved in the infrastructure.

```
#%% Material impact calculations
path = r'C:\Users\Robert\Documents\Industrial Ecology\Jaar 2\Thesis\Python\Results\Comparison\
       Leiden-The Hague\Leiden_Impact_Biogas_Heat_Pumps.xlsx'

# Impact calculation for elec generator
material_names = df_elec_generator_result.columns.values.tolist() # Select the names of columns
del material_names[0:4] # Delete non material rows
# Select only the materials from database which are relevant for this scenario
df_material_impact = material_impact.loc[:,material_names]
material_list = list(df_elec_generator_result.iloc[6,4:]) # Select the totals of materials from summary tab
df_material_impact = df_material_impact * 1000 # multiply by 1000 for impact per kg to impact per tonne
df_material_impact *= material_list # Multiply the material totals with the impact catagories
df_material_impact['Total'] = df_material_impact.sum(axis=1) # Add totals row
df_material_impact.rename(index={0:'Acidification [kg SO2-eq]', 1:'Climate change [kg CO2 eq]',
                                 2:'Eutrophication [kg PO4 eq]', 3:'Freshwater aqua [kg 1,4 DCB eq]',
                                 4: 'Human toxicity [kg 1,4 DCB eq]', 5:'Photochemical [kg ethylene eq]',
                                 6: 'Resource depletion [kg antimony eq]', 7:'Ozone [ kg CFC-11 eq]',
                                 8: 'Terrestrial ecotoxicity [kg 1,4 DCB eq]' }, inplace = True)
egen = list(df_material_impact['Total'])
# Write data to excel
writer = pd.ExcelWriter(path, engine= 'openpyxl')
df_material_impact.to_excel(writer, sheet_name='Elec generator')
writer.save()
writer.close()
# Impact calculation for elec network
material_names = df_elec_network_result.columns.values.tolist() # Select the names of columns
del material_names[0:4] # Delete non material rows
# Select only the materials from database which are relevant for this scenario
df_material_impact = material_impact.loc[:,material_names]
material_list = list(df_elec_network_result.iloc[11,4:]) # Select the totals of materials from summary tab
df_material_impact = df_material_impact * 1000 # multiply by 1000 for impact per kg to impact per tonne
df_material_impact *= material_list # Multiply the material totals with the impact catagories
df_material_impact['Total'] = df_material_impact.sum(axis=1) # Add totals row
df_material_impact.rename(index={0:'Acidification [kg SO2-eq]', 1:'Climate change [kg CO2 eq]',
                                 2:'Eutrophication [kg PO4 eq]', 3:'Freshwater aqua [kg 1,4 DCB eq]',
                                 4: 'Human toxicity [kg 1,4 DCB eq]', 5:'Photochemical [kg ethylene eq]',
                                 6: 'Resource depletion [kg antimony eq]', 7:'Ozone [ kg CFC-11 eq]',
                                 8: 'Terrestrial ecotoxicity [kg 1,4 DCB eq]' }, inplace = True)
enet = list(df_material_impact['Total'])
    # Write summary to Excel
book = load_workbook(path)
writer.book = book
df_material_impact.to_excel(writer, sheet_name='Elec network')
writer.save()
writer.close()
# Overall impact calculation
material_names = df_material_summary.columns.values.tolist() # Select the names of columns
del material_names[0:4] # Delete non material rows
# Select only the materials from database which are relevant for this scenario
df_material_impact = material_impact.loc[:,material_names]
material_list = list(df_material_summary.iloc[4,4:]) # Select the totals of materials from summary tab
df_material_impact = df_material_impact * 1000 # multiply by 1000 for impact per kg to impact per tonne
df_material_impact *= material_list # Multiply the material totals with the impact catagories
df_material_impact['Total'] = df_material_impact.sum(axis=1) # Add totals row
df_material_impact.rename(index={0:'Acidification [kg SO2-eq]', 1:'Climate change [kg CO2 eq]',
                                 2:'Eutrophication [kg PO4 eq]', 3:'Freshwater aqua [kg 1,4 DCB eq]',
                                 4: 'Human toxicity [kg 1,4 DCB eq]', 5:'Photochemical [kg ethylene eq]',
                                 6: 'Resource depletion [kg antimony eq]', 7:'Ozone [ kg CFC-11 eq]',
                                 8: 'Terrestrial ecotoxicity [kg 1,4 DCB eq]' }, inplace = True)
df_material_impact['Elec gen sub'] = egen # Add subtotals
df_material_impact['Elec net sub'] = enet
df_material_impact['Heat gen sub'] = hgen
df_material_impact['Heat net sub'] = hnet

    # Write summary to Excel
book = load_workbook(path)
writer.book = book
df_material_impact.to_excel(writer, sheet_name='Total')
writer.save()
writer.close()
```

Appendix B: Pipes and cables dimensions

The material, inner diameter and thickness of the pipes are given. Data in these tables will be coupled to the geospatial data which is acquired from the network operator.

Table 16 Natural gas and district heating pipes. Dimensions based on geospatial datasets by Liander (2019) and (SET Ltd., 2016). HTL = Hoofdtransportleidingnet (main transport network), PVC = Polyvinyl chloride, PE = Polyethylene.

Natural Gas				
Type	**Material**	**Diameter [mm]**	**Thickness [mm]**	**Comment**
Long distance	Steel	400	16	HTL pipes
High pressure	Steel	150	7.11	
Low pressure	PVC	200	14.7	Length > 50m
Low pressure	PVC	140	9.9	Length 10-50m
Low pressure	PVC	32	4.4	Length <10m
District Heating				
Type	**Material**	**Diameter [mm]**	**Thickness [mm]**	**Comment**
Long distance	Steel & PE	500	10 & 80	“Warmterontonde”
Low pressure	Steel & PE	300	7 & 56	Length > 50m
Low pressure	Steel & PE	150	3.9 & 37	Length 10-50m
Low pressure	Steel & PE	50	2.5 & 30	Length < 10m

Table 17 Electricity cables. Dimensions of medium and high voltage cables based on geospatial datasets by Liander (2019). Low voltage dimensions are based on Liander (2019) and data provided by installation companies.

Cable type	**Material**	**Core area [mm2]**	**Thickness insulation [mm]**	**Comment**
High voltage	Aluminium	400	8	
High voltage	Copper	210	8	
Medium voltage	Aluminium	240	8	
Medium voltage	Copper	95	8	
Low voltage	Aluminium	150	8	Length >50m
Low voltage 1x40A	Copper	10	6.3	Standard residential connection
Low voltage 3x25A	Copper	20	7.3	Medium residential connection
Low voltage 3x35A	Copper	50	9.2	Heavy residential connection

Appendix C: Woningwijzerwinkel Energy Labels

Bouwjaar: voor 1930

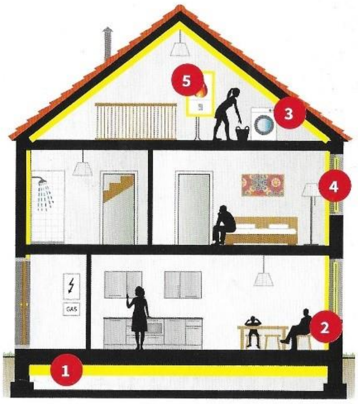
In deze bouwperiode werden er nog geen eisen gesteld aan de energiezuinigheid van woningen en er werd ook nog geen spouwmuur toegepast.

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?



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

Bouwjaar: 1930 tot 1945

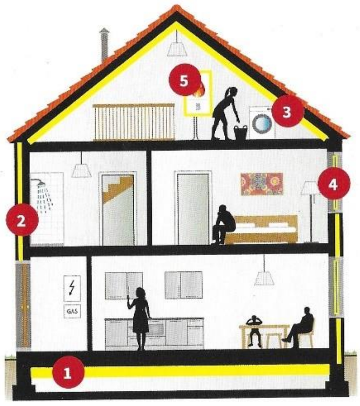
In deze bouwperiode werden er nog geen eisen gesteld aan de energiezuinigheid van woningen. Na 1930 werden er spouwmuren toegepast.

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?



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

Bouwjaar: 1946 tot 1964

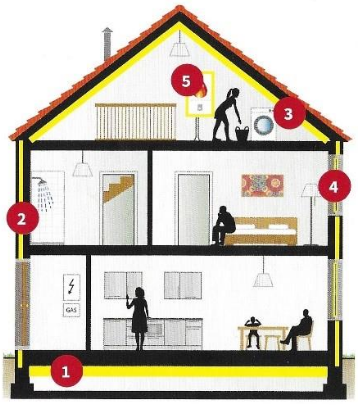
In deze bouwperiode werden er nog geen eisen gesteld aan de energiezuinigheid van woningen. Opkomst van systeem- / betonbouw.

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: GF 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

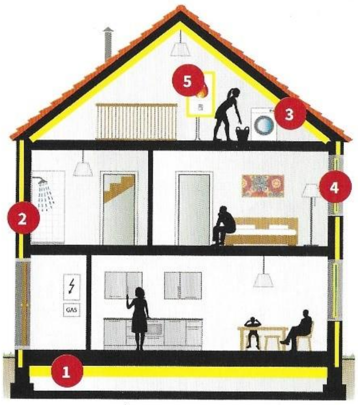
In deze bouwperiode werden er eisen gesteld aan de energiezuinigheid van woningen al waren deze naar huidige maatstaven niet hoog. Vanaf 1975 was de minimale isolatie eis voor dak- en gevel RC = 1,3 m²K/W.

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

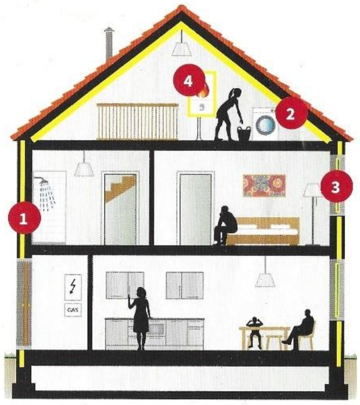
In deze bouwperiode werden er eisen gesteld aan de energiezuinigheid. De woningen zijn voorzien van dak-, gevel- (Vanaf 1983: RC = 1,3 m²K/W, vanaf 1988: RC = 2,0 m²K/W) en vloerisolatie (RC = 1,3 m²K/W).

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

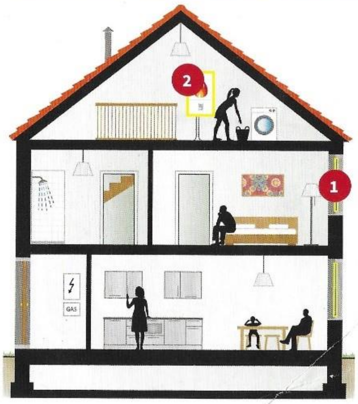
De wonigen uit deze bouwperiode zijn goed geïsoleerd. De minimale eis voor gevel, vloer en dakisolatie was RC = 2,5 m²K/W. Ook werden de woningen al met dubbelglas opgeleverd.

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 efficïent 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 D: Material inventory

Heating transport components:

Component[tonnes/km]	Sources	ceramic brick	concrete	iron	limestone	plastic PE	plastic PVC	steel
District heating pipe	Oliver-Sola et al., 2009	17.900	57.600	1.786	1.360	2.350		11.715
Natural gas pipe	Oliver-Sola et al., 2009	1.790	32.522	0.165	0.136	4.090		
Natural gas high pressure 150 mm steel	Gasunie Transport Services, n.d.							13.166
Natural gas 200 mm	Oliver-Sola et al., 2009						6.526	
Natural gas 140 mm	Gasunie Transport Services, n.d.						3.081	
Natural gas 32 mm	Gasunie Transport Services, n.d.						0.302	
District heating 300 mm	SET Ltd., 2016					27.669		26.245
District heating 150 mm	SET Ltd., 2016					9.392		7.301
District heating 50 mm	SET Ltd., 2016					2.937		1.541
Pumps and/or Surface box [tonnes/unit]	Oliver-Sola et al., 2009	1.790	0.044	0.301	0.136			
Warmterontonde pipe 500mm	Unity, 2019					65.076		62.592
Natural gas HTL pipe 400mm	Gasunie Transport Services, n.d.							79.309

Heating generation components:

Component[tonnes/MW]	Sources	aluminium	ceramic brick	chromium	concrete	copper	glass	nickel	plastic PE	steel	stone wool	wood
Biogas production	Ecoinvent 3.4			0.026						0.348	0.005	
Natural gas drilling and production	Ecoinvent 3.4											
Combined heat and power plant	Ecoinvent 3.4	0.143	3.586	0.213	28.857	0.043	0.151	0.094	0.227	6.197	0.454	
Anaerobic digestion biogas production	Ecoinvent 3.4				0.009							0.002

Heating in-house components:

Component [tonnes/dwelling]	Sources	aluminium	brass	cardboard /paper	chromium	copper	Glass fibre	nickel	Plastic PE	Plastic PUR	Plastic PVC	rubber	steel	wood
Dwelling boiler + manometer	Oliver-Sola et al., 2009		0.0002		0.0015	0.0084	0.0040	0.0007			0.0064		0.0251	
Air-source 10 kW COP =2.8	Greening & Azapagic (2012)					0.0352			0.0005		0.0016	0.0160	0.1520	
Heat exchanger + flow limiter	Oliver-Sola et al., 2009	0.0007	0.0003	0.0031		0.0216			0.0014	0.0027	0.0044		0.0254	0.0080

Electricity transport components:

component[tonnes/km]	Sources	aluminium	copper	glass fibre	insulation material	plastic PE	plastic PVC	porcelain	resin	steel	tungsten	wood
Transformer 315 kVA [tonnes/unit]	Jorge et al. 2012	0.200			0.060			0.011		0.857		
Alu highV	Nexans, n.d.	1.084					1.530					
Cu highV	Nexans, n.d.		1.882				1.044					
Alu medV	Nexans, n.d.	0.650					1.284					
Cu medV	Nexans, n.d.		0.851				0.823					
Alu lowV	Nexans, n.d.	0.407					1.121					
Cu lowV 1x40A	Liander & Eland Cables, 2019		0.090			0.098						
Cu lowV 3x25A	Liander & Eland Cables, 2019		0.179			0.146						
Cu lowV 3x35A	Liander & Eland Cables, 2019		0.448			0.267						
Transformer 63/250 MVA [tonnes/unit]	Jorge et al. 2012	0.994	21.294	0.555	0.950			1.172	0.094	74.209		0.945
66 kV Wind turbine connect sea		3.252				3.364						
10 kV wind turbine connect land		0.813				1.343						
16/20 MVA transformer [tonnes/unit]		0.094	8.673					0.125	0.058	20.417	0.002	0.517

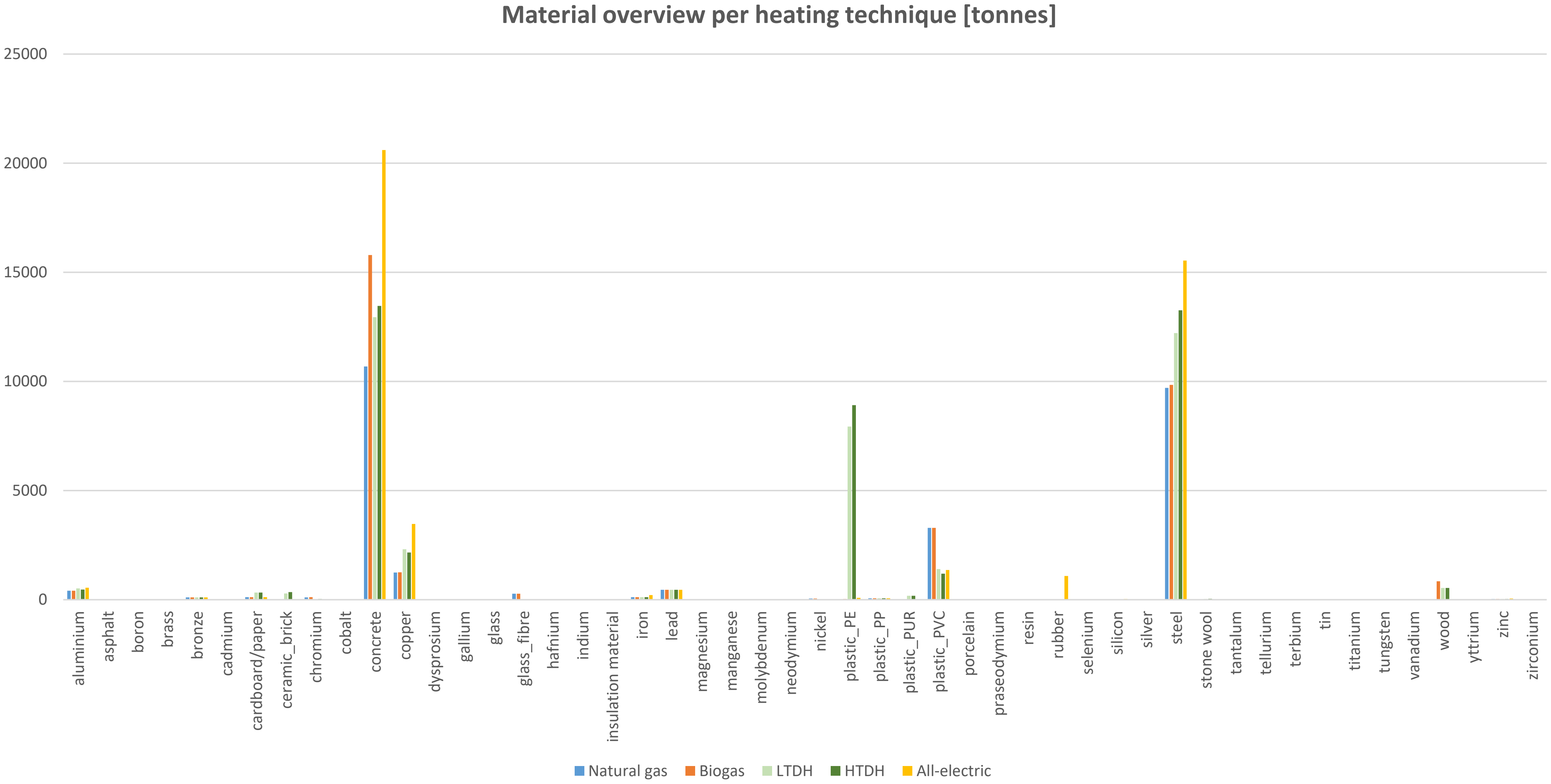
Electricity generation components:

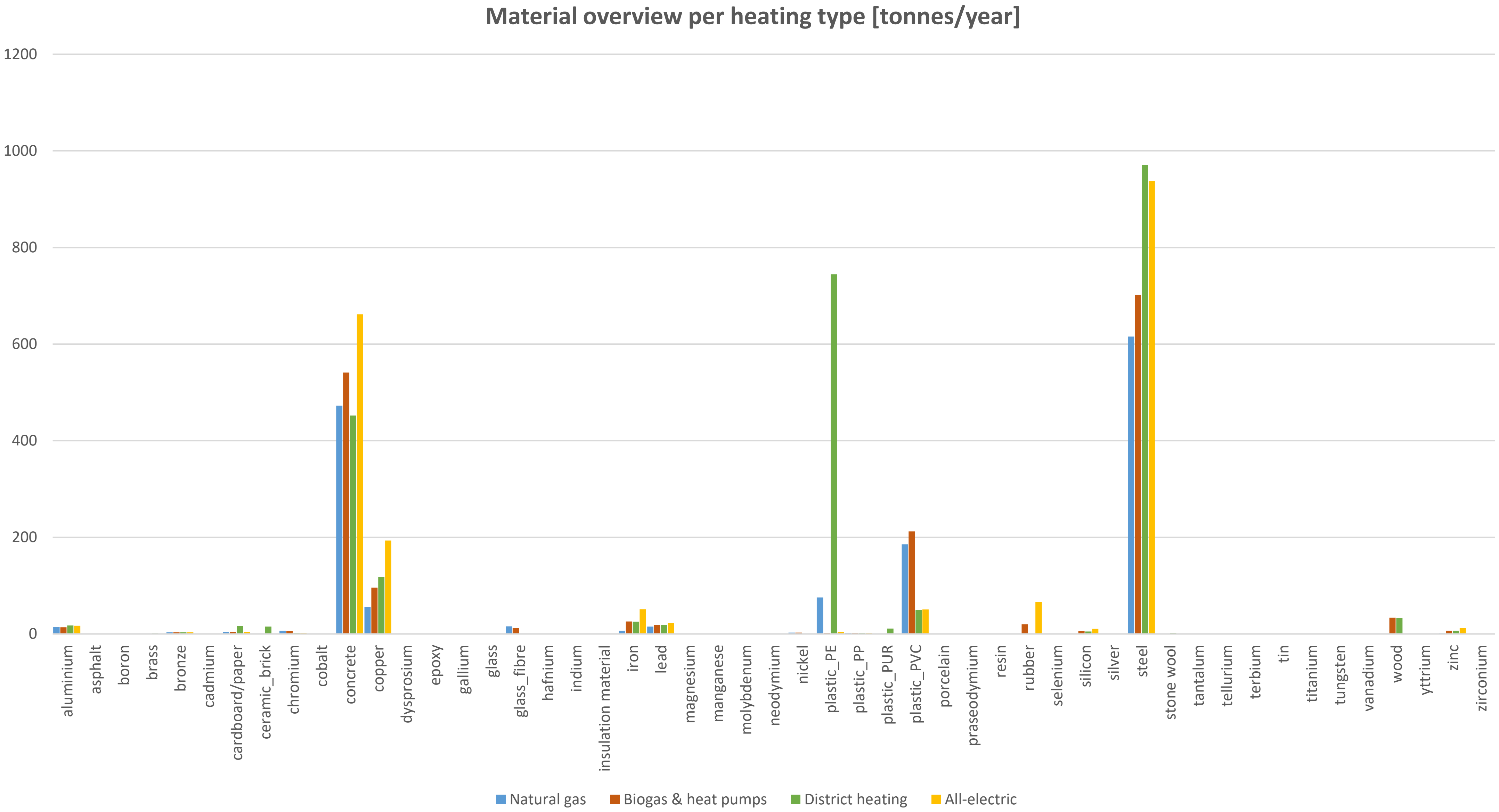
Component [tonnes/MW]	Sources	aluminium	boron	cadmium	chromium	cobalt	concrete	copper	dysprosium	epoxy	gallium	glass	Glass fibre	indium
Solar c-Si	van Exter et al., 2019	0.102						3.442						0.005
Solar CdTe	van Exter et al., 2019	0.102		0.081				5.181						0.008
Solar CIGS	van Exter et al., 2019			0.001				0.234			0.005			0.029
Wind DD onshore	Ecoinvent 3.4 & Exter et al., 2019	0.315	0.007		0.846		59	2.014	0.020					
Wind DD offshore	Ecoinvent 3.4 & Exter et al., 2019	0.395	0.007		0.846		8.000	3.798	0.020					
Wind Gear onshore	Ecoinvent 3.4 & Exter et al., 2019	0.315	0.001		0.846		59	2.014	0.003					
Wind Gear offshore	Ecoinvent 3.4 & Exter et al., 2019	0.395	0.001		0.846		8.000	3.798	0.003					
Bio/waste PP	Ecoinvent 3.4 & Moss et al., 2011	0.255			0.138	0.201	199.900	0.050						
Coal PP	Ecoinvent 3.4 & Moss et al., 2011	1.000			0.138	0.201	259.400	1.500						
Gas PP	Ecoinvent 3.4 & Moss et al., 2011	0.925			0.002	0.002	34.860	0.925						
Nuclear PP	Ecoinvent 3.4 & Moss et al., 2011	0.200		0.001	0.427		354.900	1.470						0.002
Average Solar panel	van Exter et al., 2019, Kannan, 2006. & Ecoinvent 3.4	0.097		0.004				3.369						0.006
Average wind onshore	Elsam, 2004 & Ecoinvent 3.4 & Elsam, 2004	0.315	0.004		0.846		59	2.014	0.012					
Geothermal PP	Ecoinvent 3.4	0.146			0.013		15.104	0.107		0.007		0.004	0.234	

Component [tonnes/MW]	iron	lead	manganese	molybdenum	neodymium	nickel	Plastic PP	Plastic PVC	praseodymium	selenium	silicon	silver	steel
Solar c-Si		0.072									3.787	0.041	
Solar CdTe													
Solar CIGS										0.064			
Wind DD onshore	22.405		0.057	0.126	0.202	0.427			0.035				116.667
Wind DD offshore	22.405	5.255	0.057	0.126	0.202	0.427			0.035				116.667
Wind Gear onshore	22.002		0.057	0.126	0.037	0.427			0.004				116.667
Wind Gear offshore	22.002	5.255	0.057	0.126	0.037	0.427			0.004				116.667
Bio/waste PP			0.007	0.015	0.002	0.067							33.550
Coal PP			0.007	0.015		0.067							76.950
Gas PP						0.016							
Nuclear PP		0.004		0.071	0.002	0.256						0.008	
Average Solar panel		0.065								0.003	3.409	0.037	
Average wind onshore	22.204		0.057	0.126	0.120	0.427			0.020				116.667
Geothermal PP	1.612			0.001		0.012	0.023	0.022					3.879

Component [tonnes/MW]	**stone wool**	**tantalum**	**tellurium**	**terbium**	**tin**	**titanium**	**tungsten**	**vanadium**	**yttrium**	**zinc**	**zirconium**
Solar c-Si											
Solar CdTe			0.084								
Solar CIGS			0.005		0.006						
Wind DD onshore				0.007						5.450	
Wind DD offshore				0.007						5.450	
Wind Gear onshore										5.450	
Wind Gear offshore										5.450	
Bio/waste PP		0.001				0.023	0.019	0.003			
Coal PP		0.001				0.023	0.019	0.003			
Gas PP											
Nuclear PP					0.005	0.002	0.005	0.001	0.001		0.031
Average Solar panel			0.004								
Average wind onshore				0.004						5.450	
Geothermal PP	0.435										

Appendix E: Material graphs




Material overview per heating type [tonnes/year]
1200
1000
800
600
400
200
0
aluminium
asphalt
boron
brass
bronze
cadmium
cardboard/paper
ceramic_brick
chromium
cobalt
concrete
copper
dysprosium
epoxy
gallium
glass
glass_fibre
hafnium
indium
insulation material
iron
lead
magnesium
manganese
molybdenum
neodymium
nickel
plastic_PE
plastic_PP
plastic_PUR
plastic_PVC
porcelain
praseodymium
resin
rubber
selenium
silicon
silver
steel
stone wool
tantalum
tellurium
terbium
tin
titanium
tungsten
vanadium
wood
yttrium
zinc
zirconium
Natural gas
Biogas & heat pumps
District heating
All-electric