DELFT UNIVERSITY OF TECHNOLOGY
AND UNIVERSITY OF LEIDEN

MASTER THESIS

Urban Energy Flow Analysis for transition towards sustainable cities

A case study on the heat transition in the Amsterdam Metropolitan Area

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Author:
Dirk Verweij

Supervisors:
Prof. dr. ir. Arjan van Timmeren
Prof. dr. Kornelis Blok
ir. Michiel Fremouw
Dr. Ivo Wenzler

A thesis submitted in fulfillment of the requirements for the degree of the joint master degree of Industrial Ecology at Delft University and Leiden University

November 14, 2017

Abstract

This thesis describes the energy flows and the environmental improvement possibilities of the Amsterdam metropolitan area (AMA), using district heating as thermal energy supply system. The main challenge in this research is to find an appropriate thermal supply system that can serve the required heat while increasing the sustainability in its entirety. The research presents the environmental improvements and analyzes the design parameters of different proposed technologies. The results indicate that different heat supply configurations can lead to sustainable improvements, mainly reducing the environmental impact of the following two categories: abiotic depletion and global warming potential. The spatial analysis, an important analysis in this research, focuses on suitable locations for the connection to the district heat network (DHN). According to the results, the locations that are best suited to connect to the DHN differ for each applied methodology. However, most of the locations are found in or near the larger cities of the AMA.

Summary

In recent years, the topic of sustainability has become very important and governments did place sustainability high on their agenda. A global agreement is signed, known as the Paris Agreement, to limit the release of greenhouse gas emissions in order to combat climate change. One way to achieve these goals is to reduce the thermal energy consumption which causes a large production of emissions. Currently, most of the metropolitan areas rely on unsustainable energy generators for their thermal energy supply and there is a transition needed to replace these old mechanisms for renewable sources.

This research thesis focuses on the Amsterdam Metropolitan Area (AMA), which includes 33 different different municipalities. Amsterdam wants to expand their district heat network to improve the sustainability of the thermal energy supply in the AMA to meet the Paris agreements. The main goal is to analyze all different thermal energy flows, and identify strategies to create a sustainable thermal energy supply by expanding the district heat network. The following research question is used as guidance in the analysis:

"How can an extended heating district network of the Amsterdam Metropolitan Area best be designed, and serve the thermal energy consumption of its economic sectors and household use, while improving the environmental performance of the thermal energy production."

Five distinct steps are performed to answer the research question. Each step requires different methods and relies on different parameters. The core methodologies that are used in the analysis are the energy flow analysis (EFA), the life cycle assessment (LCA) and the geographical information system (GIS). The combinations of these techniques provide the analysis, visualization and integration of the empirical data to investigate a possible design to expand the district heat network.

In the first step of this research the energy flows have been investigated for multiple sectors and the 33 different municipalities that belong to the AMA. The EFA quantifies the energy flows in urban areas and classifies them in different sectors based on the ISIC (Dutch: SBI) sectors. This classification aggregates the sectors in eleven main sectors. The residential sector is added as the twelfth sector to answer the first sub-question. In addition to the different sectors, the energy flows in all municipalities are analyzed to quantify the direct energy use, conversion losses and final energy use in the metropolitan area. The focus of the EFA lies on the space and tap water heating; therefore, only low-temperature heat is considered.

The supply of heat in the AMA is limited to two main thermal energy suppliers. Most of the thermal energy is delivered by the gas network. This network is connected to all buildings in the AMA and supplies natural gas to high efficiency condensing boilers. The gas boilers convert the natural gas to heat by combustion. Secondly, the source of the thermal energy in the studied area is the supply of heat via the district heat network. This network is delivers heat to the municipalities Almere, Amstelveen, Amsterdam, Diemen, Lelystad, Purmerend and Zandvoort and connects respectively 11% percent of all urban constructions of the case area. Hence, this is higher than the Dutch connection average that reaches 4%. This implies approximately 120.100 district heat network connections in the AMA. The heat in the district heat network comes from different fuel sources which are natural gas, waste incineration, biomass, geothermal energy and biogas.

The second step elaborates on the environmental impact of the current processes. These processes are; natural gas production, natural gas combustion in CHP plants, natural gas combustion in high efficiency condensing boilers, waste incineration in CHP plants, biomass combustion in CHP plants, biogas combustion in CHP plants and geothermal energy production. Matching LCA study processes are selected from the Ecoinvent database, based on the characteristics of the processes.

Then, ten impact categories are created with the EFA-LCA approach and four categories are used as key performance indicators (KPI). The four categories together present the baseline. This baseline is used to create an environmental impact profile of the current state of the used technologies, and to evaluate the technological improvements given in chapter 5. The selected impact categories for the KPIs are based on the environmental priorities of the AMA. The environmental priorities focus mainly on the reduction of CO_2 emissions and smog. Therefore, the KPIs selected are; abiotic depletion, acidification, global warming (GWP 100) and photochemical oxidation. With these KPIs the cumulative emissions, expressed in mass quantities, will be computed.

After the creation of the environmental impact baseline the locations of the emissions are identified by performing a spatial analysis. The spatial analysis will visualize the emitted emissions in the map of the AMA. The data that contains the gas consumptions in combination with their geographical boundaries are used for the spatial analysis. Four maps, all representing the four different KPI selected, will be made. Additional, a second map of the global warming emissions is created. This map excludes the emissions of the power plants. This makes it possible to identify the neighborhoods that produce the largest amounts of emission in relation to each other.

In the third step, the technological improvements, geothermal applications, biomass power plants, biogas power plants, hydrogen power plants and floating phase changing materials, are analyzed.

The deployment of geothermal applications already exist in the Netherlands. This technology is mostly developed for the agriculture industry, requiring large amounts of heat. The only geothermal system currently in use is the "Haagse Aardwarmte Leyweg" in the Hague. The second geothermal installation is already in construction, and located in Haarlem. This installation will reach a capacity of 33 MW_t during peak hours. Also calculations on potential production capacities in the AMA show that a geothermal installation with a capacity of 34 MW_t is plausible, provided that an electrical pump is available. The sustainability of geothermal energy is sometimes called into question due to the methane production and the limited lifetime. However, with a lifetime of more than 40 years most of the scientists consider this technology to be sustainable. The impact assessment on this technology indicate that environmental improvements are possible using geothermal energy.

The biomass technique is based on wood-chips and pruning wood wastes. Emissions of the biomass plants are often regarded to be carbon neutral. However, these emissions can still yield negative effects on the air quality of urban areas. The environmental profile of biomass shows that reductions on most of the KPIs can be reached. A disadvantage is the environmental impact in the photochemical oxidation category.

The use of biogas only attains a small share in the baseline year. This gas is currently obtained from sewage treatment plants. With thirteen different sewage treatment plants expansion of biogas production can grow. However, the production of biogas from current sewage installations requires additional energy, which makes it less efficient. In addition, the growing potential is limited and producing large quantities is therefore challenging. Biogas can be used in traditional gas turbines, due to the similar heat contents in comparison with natural gas. Hence, existing infrastructure can be maintained which involves environmental benefits.

Hydrogen is suited to use as a fuel in combustion turbines provided that certain adjustments are made. Hydrogen potentially emit no farm-full emissions after ignition. Therefore, this energy carrier can lead to sustainable energy delivery. However, the production of hydrogen currently requires more energy than it can deliver. Therefore, using hydrogen as heating technology is not feasible. Only if future production methods are constructed, e.g. hydrogen production from biological processes, this technology could lead to a sustainable energy supply.

The use of phase changing materials (PCM) is the last technology that is considered in this study. PCM is the term for substances that can store energy during phase transition. From improvement research, it turns out that this technique is still in the development stage. Temperatures that are required for the Dutch DHN are not attained. Besides that, a large number of floating vessels is needed to have a meaningful contribution in the thermal energy supply.

In the fourth step, the total improvement relating to the sustainability of the thermal energy supply configurations in the AMA is assessed. The established configurations of the heat supply will change due to the increasing share of sustainable technologies. Therefore, three new energy configurations are proposed and elaborated on their environmental performance. The energy configurations proposed are; BAU, Realistic and Optimistic. These three configurations give insight to what extent potential environmental reductions are possible. The goal of the configurations is to achieve a maximum environmental impact reduction, with limited infrastructural changes. The environmental impact of each configuration is assessed and compared with the baseline of the AMA. This gives valuable information about the potential of the environmental improvements in its entirety.

The current thermal energy supply configuration exists mostly of supply from natural gas. This fossil fuel has to be replaced by renewable sources to improve the sustainability in the AMA. Also the use of waste incineration is phased out due to the relatively high emissions occurring from the combustion of waste. In the composed BAU configuration no changes in technology configurations, besides the phase out of waste, are implemented. Only the share per technology is changed. The sustainable technologies will gain ground with respect to the natural gas combustion. The realistic configuration contains ambitious sustainability changes. However, no new technologies will be implemented. Most significant change within this configuration is the increase of geothermal energy and biomass combustion. The final optimistic configuration that is composed maintains the existing infrastructure, at the same time striving for the highest environmental improvements. No fossil fuels will be used in this configuration.

The three configurations are assessed on their overall impact. Although environmental improvements are reached the impact assessment gives variable results for the KPI impact categories. The results of the sensitivity analysis indicate that the emissions, that occur from natural gas combustion, have a large influence on the overall impact results.

In the final fifth step the number of buildings that potentially can be connected to expand the DHN are analyzed. A lot of DHNs in the Netherlands are currently further developed and extended. Especially in 2014 a significant increase is seen. In this year, housing corporations were stimulated to invest in sustainability caused by a rule change. This leads to more connections of their housing stocks to a DHN. The increase is expected to continue due to new policies relating to the heat supply. In 2018, regulations that obligate network operators to connect buildings to the gas network will end. Also on municipal level, policies are adopted relating to the expansion of the DHN. Recently, Amsterdam accepted a new policy stating that all building construction projects will be connected to the DHN, unless analysis shows that circumstances are obstructing these possibilities.

In addition to the expansion of the DHN, the trade-off between heating with all electric applications are discussed. Important factors that determine the best suited solution are: cost, technical building standards and social acceptance. Urban areas, containing high energy consumptions and heat densities are quantitatively analyzed to see which neighborhoods in the AMA can potentially be connected to the DHN. This is done on both the neighborhood boundaries split up by the municipalities, and clustered areas with high concentration populated areas. In this way multiple areas are found to connect to the DHN. Connecting the identified neighborhoods may lead to considerable environmental impact savings. Therefore, the potential environmental improvement is assessed with the results obtained from the spatial analysis. The results reveal that significant reductions can be obtained on the abiotic depletion and global warming category and limited reductions on the acidification and photochemical oxidation category.

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Chapter 1

Introduction

1.1 Context

Due to the growing concerns and recognition of the influences of anthropogenic climate change, transition towards sustainable urban areas is highly desired in many metropolitan areas (Patz et al., 2005, p. 315). Creating more sustainable urban areas is often done by reducing the unsustainable energy consumption, which is the source of unwanted greenhouse gas (GHG) emissions in cities. However, energy is synergized in our urban infrastructures and is of great importance to let the society operate. Energy comes in different forms and is defined by the Oxford dictionaries as: "The property of matter and radiation which is manifest as a capacity to perform work". Energy exists in the forms electricity and thermal energy and are for the case of unsustainable energy often generated by fossil fuels such as coal, diesel oil and natural gas. It is impossible to directly eliminate the unsustainable energy generators and replace it by sustainable ones due to the high dependency on energy. Therefore, a transition where new sustainable technologies replace the conservative polluting mechanics is highly desired.

Amsterdam is one of those cities that wants to realize this transition and has set ambition goals to make Amsterdam more sustainable. Hence, Amsterdam aims to reduce CO_2 emissions by 45% in 2025 compared to the year 2012 (Municipality of Amsterdam, 2015, p. 39). The city government of Amsterdam decided in 2015 to fully focus on circular economy with respect to their sustainable policy (Kruk et al., 2015, p. 4). In the case of energy this means reductions of energy transformations and losses. Energy is often lost in the atmosphere in the form of thermal energy. In a closed cycle economy, this thermal energy is exchanged and used to, for example, heat spaces and tap water for the district heat in Amsterdam.

Currently there are many different projects which analyze the energy saving potentials for a sustainable energy transition in Amsterdam, especially in Amsterdam Southeast, e.g. "Zero Emission Cities" (Hunziker, 2017, p. 2) from the World Business Council of Sustainable Development (WBCSD) and "Energiek Zuidoost" (Implementation plan, 2013, p. 4-5) from Amsterdam smart city. These studies are mainly focused on the business areas of Amsterdam and are specifically concerned on the development of the non-residential sectors developed by partners such as the Amsterdam ArenA, IKEA Amsterdam, the head office of Nuon and the Academic Medical Centre AMC (Amsterdam smart city, 2017). Other projects, which include the residential sector, focus on creating decision support platforms such as the TRANSFORM program, which is a data driven platform that visualizes the energy input and expose sustainable potentials (Wesselink, 2015, p. 9; City of Amsterdam, 2015, p. 2). Next to the business sectors the large residential sector with its inhabitants are responsible for a significant energy demand. Significant share of this energy demand is responsible for heating. Combining all sectors result in a high-energy demand which is mainly dominated by thermal energy for space and tap water heating. The current heat supply in Amsterdam is based on natural gas and for a small percentage on heat from the district heat network (DHN). Decreasing the environmental impact associated with space heating in Amsterdam can be realized by improving the direct thermal energy supply and relating losses.

Another interesting insight is shown by the recent research of Blom et al. (2015, p. 46); they indicate that an expansion of the current district heat network into a regional network covering the entire Amsterdam Metropolitan Area (AMA) serving a significant number of households is the most efficient form of thermal energy supply. This smart thermal grid could potentially reduce the heat consumption and will reduce the financial cost of this regional approach compared to a more local approach (Blom et al., 2015, p. 46; Möller and Lund, 2010, p. 1849).

1.2 Problem definition

The topic of sustainability has become very important for the development of cities, especially in recent years. In December 2015, a global agreement to limit the release of greenhouse gas (GHG) emissions to combat the effects of climate change was signed as the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC). The most important compliance reached by this agreement is to maintain the increasing global average temperature below an increasement of two degrees (United Nations, 2015, p. 3). To reach this goal, a transition towards renewable resources is required.

Besides the motivations to combat climate change also the scarcity of the fossil fuels, producing the required energy, plays an important role. There are a lot of debates about the depletion time of fossil fuels and estimations are divergent, however, some researchers estimate the depletion time of fossil fuels to be approximately 40, 60 and 150 years for oil, gas and coal respectively, considering constant production rates (Shafiee and Topal, 2009, p. 183).

The depletion of fossil fuels and social commotions forces producers to reduce the production of fossil fuels. In the Netherlands for example, NAM produces 58.5 billion m^3 of gas of which 89% originates from the Groningen gas field in 2012 (Ministry of Economic Affairs, 2013, p. 42). The total Dutch domestic gas demand of 2012 reaches 43.6 billion m^3 (Voort and Vanclay, 2015, p. 2). Therefore, approximately 84% of the total production of NAM in Groningen could serve the Dutch gas demand. The gas extraction in the Groningen gas field has led to localized increased seismological activity which results in lots of social pressure on the Dutch politics (Scholten, Vrouwenvelder, and Steenbergen, 2016, p. 12; J. Van Wees et al., 2014, p. 211). The social commotion caused by earthquakes forced the government of the Netherlands to reduce the extraction of natural gas to 24 billion m^3 per year to limit the safety risks of the inhabitants of Groningen as much as possible (Government of the Netherlands, 2016, p. 1).

To meet the Paris agreements and enable the gas reductions, the Netherlands has set high targets to reduce the thermal energy consumption and decrease its associated emissions (Kamp, 2015, p. 4). The thermal energy transition should lead, step by step, to a complete disconnection of natural gas in 2050 in the Netherlands (Kamp, 2016, p. 5). In the AMA however, Amsterdam has announced very ambitious goals which aims to reduce their CO_2 emissions by 40% for the year 2025 compared to the annual emissions in 1990 (City of Amsterdam, 2015, p. 2). Also, the Amsterdam board, together with 32 private parties agreed to completely disconnect the metropolitan area of Amsterdam from natural gas by 2035 (Meer, 2016, p. 1). To reach this goal, a significant part of Amsterdam is desired to be disconnected by 2030.

The main problems concerning the urban heat supply can be best described by:

- Fossil fuels produce high amounts of emissions which need to be reduced drastically.
- The board of Amsterdam has set ambitious targets and stated to be completely disconnected form gas by 2035 (Meer, 2016, p. 1).
- Current environmental impact is too high, and needs to be reduced. The ambitions goals of the City of Amsterdam (2015, p. 2) state that the CO_2 emissions must be cut by 40% in 2025 compared to the year 1990.

1.3 Thesis statement

The main goal of this research thesis is to analyze the direct thermal energy flows and their origins to create more efficient flows and identify strategies to create a pathway to a sustainable urban energy metabolism. By doing so sectoral and residential thermal energy consumption will be exposed to reveal the most energy consuming sectors. Exposing the demand of thermal energy in these sectors can provide useful information to make these flows more efficient. Finding solutions that enable a sustainable thermal energy flow can best been analyzed based on flows in urban metropolitans or cities. The reason for this is that the high thermal energy demand in these urban metropolitans will only increase. Urban areas are growing rapidly and it is expected that in 2050 about 80% of the world population will live in cities (Bettencourt and West, 2010, p. 912). Mainly in the north of

Europe this will result in a high thermal energy demand where the current total energy consumption of buildings is 41% of the final energy use, 30% of this consumption is originating from residential buildings (Santin, Itard, and Visscher, 2009, p. 1223). Of all this energy consumed in buildings 57% is used for space heating, and 25% for tap water heating (Santin, Itard, and Visscher, 2009, p. 1223). With these facts in mind it is evident to see that urban metro-poles are the places where changes can be made related to climate change. Therefore, the focus of this research will lie on the thermal energy demand of buildings in metropolitan areas. The thermal energy flows will be exposed and technical sustainable improvements will be made to improve the urban metabolism.

The thermal energy flow is part of a technical network system that supplies fuel and/or heat to the buildings in a metropolitan area. However, current energy flow analysis are limited due to the fact that the energy is analyzed for both electrical and thermal energy. In most analysis, these two different forms of energy are added up in the same energy category. Energy flows originating from different fuels are converted to the same unit of measurement to make it possible to add them up. Standard coal coefficients are often used to converted the types of urban energy into the same unit of measurement, because different fuel types contain contrasting heat values. This unit of measurement is often the standard coal equivalent in metric Tons carbon equivalent (Mtce) (Wright, Kemp, and I. Williams, 2011, p. 65). Therefore, the result of this analyzing methodology is that electrical and thermal energy are interconnected with each other and remains unclear how much of the energy in metropolitan areas is accounted for thermal energy. When the final thermal energy demand is known the required thermal energy needing to be generated by sustainable energy sources can be determined. Connecting these sources to the end users will be done using geographical information systems (GIS) software, which is a powerful tool to calculate and visualize these connected networks.

1.3.1 Case area

The area studied in this research will be the AMA, which includes the 33 different municipalities of Aalsmeer, Almere, Amstelveen, Amsterdam, Beemster, Beverwijk, Blaricum, Bloemendaal, Diemen, Edam-Volendam, Gooise meren, Haarlem, Haarlemmerliede en Spaarnwoude, Haarlemmermeer, Heemskerk, Heemstede, Hilversum, Huizen, Landsmeer, Laren, Lelystad, Oostzaan, Ouder-Amstel, Purmerend, Uitgeest, Uithoorn, Velsen, Waterland, Weesp, Wijdemeren, Wormerland, Zaanstad and Zandvoort (Hylkema et al., 2016, p. 11). These municipalities will be studied on their thermal energy consumption. In Industrial ecology sustainability on urban scales is often measured based on biophysical approaches of both material and energy analysis. Material transformation focuses on the transformation of materials from their original state into more usable states by using energy, and finally the materials are released as waste. Energy, used to produce the materials, is on its turn degraded into waste heat and emissions (Ruth, 1995, p. 100). In this study the focus will be on the analysis of energy. Therefore, the selected area will be analyzed on their direct thermal energy consumption. This area is selected because it already contains a district heat network. In addition, it has a sufficient amount of data and provides valuable research opportunities which can build on researches previously performed. The current thermal demand of this area will be analyzed based on the natural gas use and the fuels that deliver heat via the district heat. The AMA, with its municipalities in 2015, and the current district network are presented in Figure 1.1. The agglomeration of municipalities of the metropolitan area of Amsterdam is changed in 2016 (Hylkema et al., 2016, p. 12). Therefore, the number of municipalities changes from 36 to 33 due to the coalescence of the municipalities Bussum, Muiden and Naarden into Gooise-meren and Zeevang who fused with Edam-Volendam.

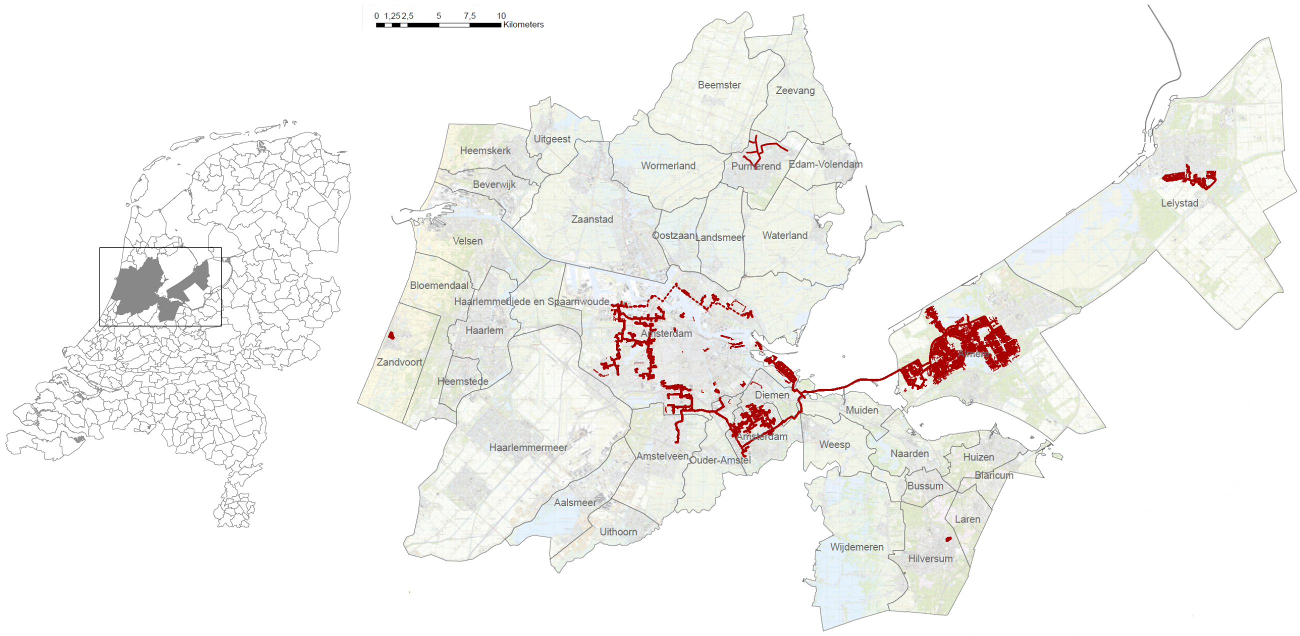

FIGURE 1.1: Left: location of the AMA. Right: Heat district network of the Amsterdam metropolitan area (Voskuilen and Bremer, 2016, p. 14).

The AMA is distributed over a large part of the provinces Noord-Holland and Flevoland. The metropolitan area grows with an amount of approximately 22.500 persons per year, relating to the amount of inhabitants in AMA. This is more than twice the growth rate compared to the Netherlands (Hylkema et al., 2016, p. 17; Kruk et al., 2015, p. 9). Municipalities such as the Haarlemmermeer and Almere are the fastest growing areas which also contain many building construction plans (Musterd, Bontje, and Ostendorf, 2006, p. 369; Voskuilen and Bremer, 2016, p. 10). Therefore, considering the growth rates, the thermal energy consumption is likely to increase for the coming years if the isolation standards of building do not improve.

1.3.2 Knowledge gaps

Most publications that elaborate on the expansion of the heat district of Amsterdam feature energy analysis, urban metabolism and/or energy potentials of thermal energy. As is often the case with similar publications the link to regional implementations and district network characteristics are missing. Regional implementations where thermal energy potentials are elaborated, combined with strategies to implement existing technologies can improve the quality of research. Including technological applications will help to decrease the gap between ecologist, urban architects and engineers.

1.4 Research Question

As can be obtained in the thesis statement and the selected case area the main goal of this thesis research is to analyze and improve the thermal energy flows of the metropolitan area of Amsterdam. By analyzing the flows of the thermal energy consumption more efficient supply flow can be created to serve the demand. This can be encompassed by the following research question:

"How can an extended heating district network of the Amsterdam Metropolitan Area best be designed, and serve the thermal energy consumption of its economic sectors and household use, while improving the environmental performance of the thermal energy production."

The research question can be answered by formulating certain sub-questions. These sub-questions are listed below:

1. What is the final thermal energy consumption in the Amsterdam metropolitan area and its economic sectors and household use?

2. What are the options to reduce the environmental impact of the thermal energy production and supply in the Amsterdam metropolitan area?

3. Which thermal energy configurations can best be implemented in the thermal energy facilities of the Amsterdam metropolitan area and serve the sustainability strategy?

4. Which buildings need to be connected to the district heat network to reach the most efficient thermal energy supply in the Amsterdam metropolitan area?

Chapter 2

Methodology

2.1 Methods

This section will describe the core analysis and tools used which will result in the methodological approach. In addition, the theoretical background and important parameters will be described here.

2.1.1 Energy Flow Analysis

The Energy Flow Analysis (EFA) used to analyze energy flow is similar to the better-known Material Flow Analysis (MFA). Hence, the EFA model also tries to expose and account the energetic metabolism of urban areas (H. Haberl, 2001, p. 14). EFA specifically analyzes the energy carriers that flow through an urban area. The methodology considers the physical law of mass, which expresses that mass can't be lost, i.e. the input must equal the output within the system (Schneider et al., 2002, p. 3). Energy flow balances are used to study the metabolism of cities as well as entire industries. Equal to the MFA approach the EFA methodology contains three generic process steps: system definition, process chain analysis/ quantification and evaluation of results (Gregory, 2006, p. 13). Parameters used to perform the EFA are described below and schematically visualized in Appendix A.

Systems definition; within this subsection the targets are formulated and the primary objectives are defined. Also, spatial, temporal and functional units of the energy flow are defined. The spatial scope is based on a regional space with a geographically bounded area. Within this area all energy flows and processes such as transformation and losses are analyzed. The functional scope focus on the substance life cycle, and its servings to a specific area, regardless of the location. The temporal scope explains the time frame and duration of the studied area. Usually a time frame of one year is chosen, depending on the data availability. In this step, also the type of energy carriers or energetic metabolism of an urban area is considered.

Process Chain Analysis/ Quantification; defines processes using accounting and balancing. By using mass balances of the selected flows the input and outputs in the system are determined. This step gives an overview of the flows and stocks. In this stage, the data is selected and gathered. When the data is complete the modeling of the flows can be applied. There are three modeling possibilities; bookkeeping, static modeling and dynamic modeling. The type of modeling used in this study is bookkeeping, which gives an overview of the flows and stocks of the urban area based on the mass balances.

Evaluation of results; in the last step, the models are examined on their robustness to eliminate uncertainties. This step is performed using a sensitivity analysis. In this way it is possible to check if inaccuracies in the dataset and mass balances do affect the results. This stage is often used for decision making and will strengthen the conclusions. The coefficients of equivalent are often paraphrased into better understandable units to make the outcomes more comprehensible. This study will present the outcomes in tera joules (TJ) based on the caloric values of the different substances analyzed, given in Appendix B.

2.1.2 Life Cycle Approach

An useful tool to assess the environmental impacts is the Life Cycle Assessment (LCA) tool. LCA is a favorable tool to use due to the wide considerations it comprehends. It considers the entire life cycle of a product or process and quantifies the correlated impact. Also, the assessment can be performed based on different impact categories. The combination of a EFA and LCA is not broadly used. However, a combined Material Flow Analysis (MFA) and LCA study is widely employed in the field of industrial ecology (Venkatesh, Hammervold, and Brattebø, 2009, p. 535; Rochat et al., 2013, p. 642; Silva et al., 2015, p. 159). Due the similarities between EFA and MFA, which both contain a mass based indicator, it is suitable to perform a combined EFA-LCA approach. Combining both tools will result in mass based impact categories. These impact categories can be used to analyze the current environmental performance of the metropolitan area. Therefore, adding impact categories to the outcome of the EFA will increase the environmental information and will increase the information value (Voet, Oers, and Nikolic, 2004, p. 7).

The impact categories used are the categories developed in the handbook of Life Cycle Assessment written by J. B. Guinée et al. (2002). Using these impact categories, the impact profiles of the used energy carriers are made. The impact categories are composed based on the CML 2 Baseline 2000 methodology, which is a method developed in 1992, and updated in 2000 by the Center for Environmental Studies (CML) of the University of Leiden in the Netherlands (J. B. Guinée et al., 2002, p. 5; Heijungs et al., 1992, p. 4). The CML 2 Baseline 2000 methodology describes the most important impact categories and has various normalization possibilities. The normalization set used in this study is the Netherlands (1997), which uses 1997 as reference year to contrasts the different impacts. This means that the substance equivalents per impact category are referenced to annual impacts of the year 1997 in the Netherlands per impact category. This makes it possible to compare the environmental impact profile of the thermal energy generation in the AMA with the normalization situation of the Netherlands in 1997. The CML baseline method analyses the environmental impact by the ten categories; abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, human toxicity, fresh water ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity and photochemical oxidation. Their units are listed in Table 2.1.

TABLE 2.1: CML 2 Baseline 2000 Impact categories

no.	Impact category	Unit
1	Abiotic depletion	kg Sb eq
2	Acidification	kg SO_2 eq
3	Eutrophication	kg PO_4 eq
4	Global warming (GWP 100)	kg CO_2 eq
5	Ozone layer depletion (ODP)	kg CFC-11 eq
6	Human toxicity	kg 1,4-DB eq
7	Fresh water aquatic ecotoxicity	kg 1,4-DB eq
8	Marine aquatic ecotoxicity	kg 1,4-DB eq
9	Terrestrial ecotoxicity	kg 1,4-DB eq
10	Photochemical oxidation	kg C_2H_4 eq

In the next part the content of the impact categories are explained based on the definitions given by J. B. Guinée et al. (2002, p. 63) and Heijungs et al. (1992, p. 43-46):

Abiotic depletion; abiotic resources are natural resources regarded as non-living, e.g. iron ores and crude oil. This category concerns the depletion of these resources. The impact category relates to the extraction of these resources using the Abiotic Depletion Factor (ADF) which is a factor based on the remaining reserves and the rate of extraction of a resource. The ADF uses the equation: production divided by the prospected reserves, and is compared to the reference material Antimony (Sb). Therefore, the unit of abiotic depletion is measured in kg Sb equivalent.

Acidification; acidifying pollutants have diverse impacts on biological organisms, groundwater, surface waters, soil and materials (buildings). Acidic gases like sulphur dioxide are harmful to most organisms in these ecosystems because it reacts with hydro droplets in the atmosphere which form acid rain. Therefore, acidification uses the reference unit of kg SO_2 equivalent.

Eutrophication; nutrients such as nitrogen and phosphorus are important to maintain life. However, in high concentrations an undesirable shift in the balanced diversity can occur. In water, it will lead to excessive biomass growth reducing the oxygen. This will eventually lead to contamination of water sources. Eutrophication is expressed by the unit of kg PO_4 equivalent.

Global warming (GWP 100); climate change is defined as significant changes in the statistical distribution of the atmosphere. This impact category is defined as the impact of anthropogenic GHG emissions which influences the force of radiations in the atmosphere. Best known GHG are CO, CO_2, methane, nitric oxide and ozone. The category is based on a model of the United Nations Intergovernmental Panel on Climate Change (IPCC) and expresses a potential global warming indicator for a period of 100 years (GW 100a). The increase of radiations in the atmosphere may have adverse impacts on ecosystem health, human health and material welfare. Most of these emissions contribute to the rise of temperature of the earth's surface. Strong GHG, which has significant influence on the radiations in the atmosphere, is carbon dioxide due to its frequent occurrence. Therefore, the impact category climate change is measured in kg CO_2 equivalent.

Ozone layer depletion (ODP); describes a reducing stratospheric layer, with ozone as main compound, due to anthropogenic activities. The damage on the ozone layer affected by chlorinate and brominate compounds directly affects the amount of ultra violet radiation which heats the earths surface. Different gas substances affect the amount of ozone in the atmosphere and are relativized by the reference substance kg CFC-11 equivalent.

Human toxicity; this category represents the impact of human health caused by toxic substances. This category is based on the amount of exposure of toxic substances, and the effects and health impact that occur after exposure. The reference unit used to express this category is kg DB equivalent.

Freshwater aquatic ecotoxicity; this category refers to the effects on freshwater ecosystems caused by to toxic substances. The category includes the disturbance of the diversity and biochemistry of living organisms within freshwater aquatic ecosystems. Similar to human toxicity, the reference unit used to express this category is kg DB equivalent.

Marine aquatic toxicity; this category refers to the effects in marine ecosystems caused by toxic substances. The category includes the disturbance of the diversity and biochemistry of living organisms within marine aquatic ecosystems. Similar to human toxicity, the reference unit used to express this category is kg DB equivalent.

Terrestrial ecotoxicity; this impact category refers to the effect of toxic substances on terrestrial ecosystems. This includes the diversity of ecosystems on land. The category relates to the disturbance of the diversity and biochemistry of living organisms within terrestrial ecosystems. Similar to human toxicity, the reference unit used to express this category is kg DB equivalent.

Photochemical oxidation; photochemical-oxidant formation is the formation of reactive chemical compounds, such as ozone by the action of sunlight on primary air pollutants including nitrogen oxides and hydrocarbons and is known as summer smog. These reactive chemical compounds may influence human health and ecosystems. The oxidants are mostly shaped in the troposphere under influence of ultraviolet light, through the photochemical oxidation of volatile organic compounds (VOC) and carbon-monoxide (CO) in combination with the presence of nitrogen oxides. The reference unit used to express this impact category is ethylene (C_2H_4) and is therefore measured by kg C_22_4 equivalent.

2.1.3 Geographical Information Systems

A geographical information system (GIS) is computer based software which can store and check an expose data that simulates coordinate related areas. The software can integrate geographic locations with algorithms tools to perform analysis such as network analysis, energy analysis, climate simulations and flow analysis on a data set (Girardin, 2012, p. 32). The system works with points, polylines and polygons to visualize the data. In this way maps and simulations of building and landscape designs in urban region can be made.

In this study GIS will be used to visualize the results obtained from the EFA and LCA studies. Higher level results can be obtained by visualizing the outcomes in geographical bounded areas. This will be helpful for selecting the neighborhoods that are best suited to connected to DHN. When the neighborhoods are selected GIS will be used to connect potential future heat sources with the end users located in these neighborhoods.

2.2 Integration and stepwise approach

This section describes the methodological steps that will be taken in order to answer the sub-questions. Since every step requires different research methods and parameters they will be elaborated step by step. The combination of quantitative tools such as EFA, LCA and GIS will be used as core methodologies of the research. The research will use these tools to develop and extend thermal energy systems in urban areas. The methodological tools used are analytical methods which are all originated from different academic disciplines:

- Energy Flow Analysis and Life Cycle Approach; originated from Industrial Ecology, in this research it is used to quantify the import and export flows and socio-economic stocks of energy.
- Geographical Information Systems; originated from Geosciences, in this research it will encompass the visualization and network structuring phase of the data obtained from the Energy Flow Analysis.

Hence, these techniques result in an interdisciplinary study and can be used in the pre-design phase for creating a heat district network in urban areas.

The combinations of these technical tools and techniques can be used to analyze, visualize and integrate the empirical data investigated to identify how the network should expand. This combination provides an understandable meaning for both industrial ecologists, technical engineers and urban architects which is necessary to explain the elements that different stakeholders face with respect to a changing climate. Together with the integrated tools, the research questions are answered using five steps.

2.2.1 Step 1. Energy Flow Analysis

This step will be elaborated in chapter 3, with this step sub-question 1 can be answered. The Energy Flow Analysis is used for tracking the energy balance in geographical areas and is able to consider economic and ecological processes. This method is widely used for analyzing energy balances on national, regional and industrial scale (Helmut Haberl, 2001, p. 14; C. A. Kennedy et al., 2015, p. 5985; S. Chen and B. Chen, 2014, p. 152). By tracking the energy flows, estimations of impact on the ecosystems caused by anthropogenic activities can be made (Sundkvist et al., 1999, p. 290). Indicators used for the analysis consist of the direct energy input, losses and energy consumption.

The system definition and boundaries can be defined with the earlier mentioned spatial, temporal and functional scope of the energy flow. The spatial scope of the research are the geographical boundaries of the metropolitan area of Amsterdam which includes 33 different municipalities surrounding Amsterdam. The population density is relatively high compared to the rest of the Netherlands; this area contains approximately 2.4 million inhabitants (Hylkema et al., 2016, p. 17). The functional scope is the urban energy consumption considering the entire life cycle. The temporal scope is the time period of one year. The latest possible data will be used to perform the analysis. The year selected for the study is 2015 due to the great amount of data. From this year, a base line will be created to manifest the differences in environmental impacts per thermal energy generation technology. This baseline will be created in step 2 using the impact assessment.

To answer the first sub-question the thermal energy expensed by different economic sectors of the metropolitan will be computed. This will be done by calculating the direct energy input, which is based on the final energy consumption and transmission losses. The boundaries of the different sectors is based on the Eurostat European Commission format, described by the International Standard Industrial Classifications of economic activities in the European Community, abbreviated as ISIC (Dutch: SBI) and is presented in Table 2.2 (CBS, 2017c, p, 3-6).

TABLE 2.2: ISIC of all economic activities

no.	Section	Sector description
1	A	Agriculture, Forestry and Fishing
2	B	Mining and Quarrying
3	C	Manufacturing
4	D	Electricity, Gas, Steam and Air conditioning supply
5	E	Water Supply; Sewerage, waste management and remediation activities
6	F	Construction
7	G	Wholesale and Retail trade; Repair of motor vehicles and motorcycles
8	H	Transportation and Storage
9	I	Accommodation and food service activities
10	J	Information and communication
11	K	Financial and Insurance activities
12	L	Real Estate Activities
13	M	Professional, scientific and technical activities
14	N	Administrative and Support Service Activities
15	O	Public Administration and Defense; Compulsory Social Security
16	P	Education
17	Q	Human Health and Social Work Activities
18	R	Arts, entertainment and Recreation
19	S	Other Service Activities
20	T	Activities of Households as Employers undifferentiated goods- and services-producing activities of households for own use
21	U	Activities of Extraterritorial Organizations and Bodies

For the energy flow analysis of the AMA however, an aggregated structure will be used which aggregates the above-mentioned sections into eleven different categories and is presented in Table 2.3. This aggregated selection can be identified as standard ISIC category and is known as "high-level aggregation" category (Eurostat, 2008, p. 43).

TABLE 2.3: High-level aggregation of economic activities

no.	Section	Sector description	Abbreviation used
1	A	Agriculture, Forestry and Fishing	Agriculture
2	B, D and E	Mining, quarrying and Other industry	Mining
3	C	Manufacturing	Manufacturing
4	F	Construction	Construction
5	G, H and I	Wholesale and retail trade, transportation and storage, accommodation and food service activities	Retail trade
6	J	Information and communication	Information
7	K	Financial and Insurance activities	Financial
8	L	Real Estate Activities	Real Estate
9	M and N	Professional, scientific, technical, administration and support service activities	Service activities
10	O, P and Q	Public administration, defense, education, human health and social work activities	Public administration
11	R, S, T and U	Other activities	Other activities

In the analysis of the AMA a twelfth sector will be applied, which is the residential sector. This sector is applied due to the high impact on thermal energy in urban areas. Table 2.3 also lists the abbreviations used in this research, which will be used to identify the different sectors in tables and figures.

By using the EFA it is possible to investigate multiple fuels consumed within a metropolitan area and sectors (C. Kennedy et al., 2009, p. 7297). The energy carriers investigated to count the metropolitans energy balance are all fuels that contribute to the total thermal energy consumption of the urban area. This study will focus on thermal energy carriers used for space and tap water heating only, which have a share of respectively 72.7 and 23.3% of the total gas use (Majcen, Itard, and Visscher, 2013, p. 129). Most thermal energy is generated by natural gas since 98% of the Dutch households are connected to the gas grid (Weidenaar, Bekkering, and Eekelen, 2012, p. 1). Only low-temperature heat for space and tap water heating purposes is considered within all sectors. High-temperature heat from natural gas is mostly used for industrial purposes. Therefore, efforts will be made to eliminate natural gas used for industrial purposes other than space and tap water heating. Gas consumed by cooking is responsible for only a small amount of the total gas consumption, less than 4% (Majcen, Itard, and Visscher, 2013, p. 129). Therefore, the natural gas consumed within the AMA is assumed to be only used for space and tap water heating. In the AMA the average amount of natural gas consumed is expected to be a little lower compared to the average amount of the Netherlands. This is due to the high effort that is made to invest into a heat district network. In 2015, the distribution of buildings connected to the district heating network are the municipalities Almere, Amstelveen, Amsterdam, Blaricum, Diemen, Lelystad, Purmerend and Zandvoort with respectively a percentage of 58.5, 6.8, 9.7, 7.6, 5.6, 15.6, 70.4 and 6.3 (Menkveld et al., 2017, p. 49; Niessink and Rösler, 2015, p. 69). Therefore, for this study it is assumed that all thermal energy consumed in the different municipalities is produced by either natural gas obtained by the gas grid or by the district heat network.

The following types of fuels and processes are selected to investigate their contributions to the urban thermal energy consumption; coal, natural gas, heating oil, biomass, biogas, geothermal and industrial waste. Because the different fuel types have different caloric values, all fuels will be analyzed on their energy content. The analysis performed on the energy carriers will be based on a bottom up approach.

Results: *a quantitative analysis which gives an overview of the origin and consumption of thermal energy within the sectors of the Amsterdam metropolitan area.*

2.2.2 Step 2. Impact assessment and visualization

This step will be elaborated in chapter 4, with this step the environmental performance and the current stage of technologies will be considered. In addition, this step contains the impact assessment and visualizations of the results obtained by the EFA, performed in step one. The environmental impact assessment of the thermal energy consumption will be determined with a life cycle approach based on the energy flows of the energy carriers. This type of impact assessment is chosen because it comprises the complete impact of the consumed thermal energy carriers. Significant part of the environmental impacts of the used substances occur during the production phase, therefore it is important to include the entire life cycle of the substances. Based on the impacts categories of the impact assessment the key performance indicators (KPIs) will be selected in this step. The selected KPI categories will be elected based on their relation to climate change and air quality, which are affected by the analyzed energy carriers (Fremouw, 2017).

The impact profiles of the different processes to generate heat will be modeled using Simapro software (Goedkoop et al., 2008, p. 5). By using Simapro it is possible to generate information about the environmental impact of the energy processes based on data obtained from the Ecoinvent 3 database. This database contains comprehensive environmental life cycle studies and is the largest transparent unit-process based database in the world (Wernet et al., 2016, p. 1218). Results obtained by using this database is not an exact reflection of the environmental performance of the technologies analyzed, and can contain deviations relating to the exact environmental profile. However, using this database makes it possible to retrieve insights in the environmental proportions of multiple technologies and to compare different technologies among each other.

After the impact assessment, concerning the data in step one, is completed a baseline with the impacts of the primary energy consumption will be established. The outcomes of the EFA and LCA will be visualized in multiple manners. The performance of each sector will be compared among each other using histograms for all municipalities and sectors within the AMA. The proportions of thermal energy used per sector will give some interesting results to highlight the main fuel sources used to generate the thermal energy.

QGIS software as GIS tool will be used to represent the outcomes, which will add an extra dimension when analyzing the results. Heat maps created by GIS based software will help by analyzing the area. The data, which is geographical bounded, will be presented by displaying different aspects per municipality. Maps show the highest consumption densities per municipality and most consuming sectors per municipality will be made in this step. In this way spatial analysis of the geographical data can be performed to conceive patterns which otherwise wouldn't have been found. Important performance of this step is to acquire the geographical files of all municipalities and link the obtained data to it. Data from the open sources Statistics Netherlands (CBS), statline, Energieinbeeld.nl, Stedin and Alliander will be used to obtain useful shapefiles and geographic bounded data for the required geographical area.

Results: *a quantitative impact profile per industrial thermal energy process, visualized within the geographical boundaries of the Amsterdam metropolitan area.*

2.2.3 Step 3. Technologies and improvements

This step will be elaborated in chapter 5, with this step sub-question 2 will be answered. The focus of this step lies on the potential energy generators required for the transition towards the sustainable energy supply. Potential energy sources will be investigated and elaborated. Also, the technical characteristics of the DHN will be discussed, including its most important parameters. When the amount of consumed thermal energy and the associated fuels are known the required amount of sustainable thermal energy sources can be investigated. New technological improvements will be examined on their sustainability and environmental profiles will be created per potential energy source. The environmental performance will be revalidated to the baseline created in step two. The analysis executed within this section is established by both qualitative and quantitative analysis. The current state of the discussed technologies will be based on qualitative analysis, the environmental profiles will be obtained by data from the EFA and LCAs originating from the ecoinvent database. Existing and future technologies for both the generation of thermal energy and improvement of the efficiencies are discussed. The reliability of the proposed technologies are besides assessed on three processes criteria; used raw materials, used combustion techniques and matching capacities. The criteria are qualitatively reviewed and can score from very corresponding, sufficient to inadequate. Accordingly the reliability is discussed to assure the value of the outcomes.

Results: *a selection of quantified improvements included with technological and environmental characteristics and performances.*

2.2.4 Step 4. Thermal energy configurations

This step is elaborated in chapter 6 and will answer sub-question 3. In this section the environmental improvements of supply technologies in the AMA are discussed. The environmental profiles retrieved from the environmental impact research in chapter 5 will be used to compose different thermal energy supply configurations. Three different configurations will be made and are composed with combinations of the different energy supply technologies given in step 3. Combining these combinations should lead to an improved environmental profile. The different sustainability configuration improvements used will be; business-as-usual (BAU), realistic and optimistic.

The BAU scenario describes a future development where no significant shift in interventions, operating systems or paradigms occur. Traditional operation techniques remain established. The realistic scenario describes a development of current sustainable technologies which combined will be prominently presented. However, new technologies will barely be implemented. The optimistic scenario describes a future where maximum effort is put in quick development of sustainable technologies. New sustainable unconventional technologies are embraced and implemented in the energy supply configuration.

Finally, this step describes the potential locations of the technologies and implementation implications, which could affect the technological development.

Results: *an extensive sustainability configuration to reduce the environmental impact for the thermal energy supply in the Amsterdam metropolitan area.*

2.2.5 Step 5. Geo-spatial neighborhood analysis

This is the final step and will be elaborated in chapter 7, answering sub-question 4. In the final step a spatial analysis is performed with the goal to identify possible buildings that should be connected to each other. This will be performed on the neighborhood level where these buildings are located. In order to identify which neighborhoods are best suited to connect, the final demand per neighborhood is visualized. The neighborhoods compared have the geographical boundaries of the neighborhood maps preserved by CBS (2015). The identification of the best suited neighborhoods is performed with data of the gas consumptions retrieved from Stedin and Alliander. This data only represents limited data of the residents and small and medium-sized enterprises but are nevertheless the households which currently consume natural gas. Therefore, it is suitable to investigate the potentials for the transition from gas to sustainable sources in the AMA for these particular households.

When classifying the best suited neighborhoods the density, distribution and concentration of the population are important factors and will therefore be taken into account. Also, the changes of energy demand are elaborated in this step.

Results: *an overview of best suited neighborhoods based on the thermal energy demands and potential sustainable energy supply.*

Chapter 3

Energy Flow Analysis

3.1 Data gathering

In this study, only gas use and district heat are considered as energy sources to heat the spaces and tap water of the selected, sectoral establishments and residential buildings in the Amsterdam Metropolitan Area (AMA). Data is gathered from Central bureau of Statistics (CBS) and checked with data from the Klimaatmonitor, and from open data of Alliander and Stedin (Energieinbeeld, 2017). After the analysis the data is verified with results from different researches in section 3.4. The empirical data analyzed for the energy flow analysis will be performed based on the ISIC (Dutch: SBI) sectors (CBS, 2017c, p, 3-6). For the EFA of the AMA, an aggregated structure will be used to aggregate eleven sectors into different categories. In this study a twelfth sector, the residential, is also considered.

The data of the natural gas use in the metropolitan area of Amsterdam was used to quantify the energy use of the area. The most important accounting indicators used in this EFA are quantified as direct energy consumption, conversion losses and final energy use. However, some data of the sectors are unknown, unreliable or secret. Therefore, the total gas consumption obtained from the CBS statics is (often) higher or the same as the summarized data given per sector. In some cases however, no total gas use was given. In these cases, the sum of the given sectors is used. In the cases that a lower total amount is indicated by CBS than the sum of all sectors, then the sum of the sectors is used. For the EFA only low-temperature heat is investigated for all sectors. To ensure that only low-temperature heat is used, efforts are made to exclude the high-temperature heat. For example, the gas consumption of the municipalities Amsterdam and Velsen were corrected to eliminate the gas used by the Hemweg power plant in Amsterdam, and the IJmond-1, Velsen-24 and Velsen-25 power plants in Velsen, owned by Nuon. The results of the EFA will be given as amount of energy used, in PJ, per sector and municipality. The energy values of the sectors and municipalities used to convert the gas quantities to energy are listed in Appendix B.

An important finding of the EFA is that the total gas consumption of all municipalities in the AMA together is 2.4 billion m^3 natural gas in 2015, which is equal to 83,7 PJ. Most of this energy is consumed by the residential sector, 41.4 PJ, followed by the manufacturing, 12.3 PJ. In these energy values the energy originated from DHN is excluded. When the DHN, supplied by natural gas, waste, biomass, geothermal and biogas, is added, then a total energy consumption of 162,4 PJ is reached. This amount of thermal energy is divided over 247.015 sectoral establishments and 1.110.937 residential buildings. The distribution of all buildings in the AMA per municipality can be found in Appendix C. The municipality Amsterdam covers the biggest part of the energy consumption with 59.3 PJ. It is assumed that all natural gas consumed by the boilers in the municipalities originates from Groningen, which contains a higher caloric value than the standard ISO-norm gas, and equals 35.17 GJ per 1000 m^3. The gas consumed by the power plants are assumed to consume gas with a ISO norm caloric value, which equals 31.65 GJ per 1000 m^3 (Gerdes et al., 2016, p. 86). Also the caloric values of the other energy carriers used can be found in Appendix B.

3.2 Energy carrier contribution analysis

Based on qualitative research it is obtained that most buildings in the Netherlands heat their spaces and tap water with natural gas. In 2015, 85% of the Dutch households heat their water with central heating by high condensing boilers, powered by natural gas (Gerdes et al., 2016, p. 12). Other forms of thermal energy supply used by buildings originates from local heating and electrical heat pumps with a share of respectively 9.5 and 1.5 percent (Gerdes et al., 2016, p. 12). The share of the buildings heated by the DHN in the Netherlands is relatively small, only 4% (Menkveld et al., 2017, p. 5). The proportions of used fuel types for heating buildings that are connected to the DHN are diverse. The DHN uses 74% of his thermal energy for combined heat and power (CHP) plants including auxiliary boilers (Menkveld et al., 2017, p. 51). This makes tap and space heating in the Netherlands mostly natural gas based.

Based on quantitative analysis from the empirical data retrieved of the AMA, it is obtained that the share of connections to a DHN in the AMA is larger. According to the EFA it turns out that approximately 11% of the sectoral establishments and residential buildings is connected to a DHN, which leads to a total of approximately 120.100 connections in 2015 (CBS, 2017a). Also the thermal energy supply by the DHN in AMA is, like the rest of the Netherlands, mostly natural gas based. Figure 3.1. shows the different proportions of the fuel types used as direct energy input in the 12 selected urban sectors in the metropolitan area. Geothermal energy is included in this EFA next to the selected fuel types in subsection 2.2.1 because of its upcoming proportions in delivering heat to the heat network. Heat pumps are excluded in this study due to their relative small share and the problems around data unavailability.

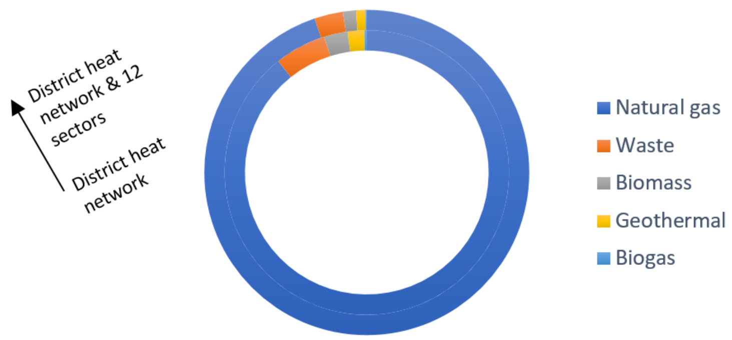

FIGURE 3.1: Proportions of energy sources used in the thermal energy consumption in AMA

The inner ring of Figure 3.1 represents the contribution of fuels used for space and tap water heating in the DHNs. The DHN in AMA is limited to the municipalities Almere, Amstelveen, Amsterdam, Diemen, Lelystad, Purmerend and Zandvoort where respectively a percentage of 58.5, 6.8, 9.7, 5.6, 15.6, 70.4 and 6.3 of the urban constructions is connected to the network in 2015 (CBS, 2017a). Based on the connection rates and the total households per municipality (given in Appendix C) this leads to approximately 46.200, 2.900, 40.400, 5.100, 24.900 and 600 connected buildings respectively. All energy sources are converted to equal unit of measurements and are compared on their energy content, based on the caloric value. This results in an energy source distribution of 89.9% natural gas, 5.9% waste incineration, 2.7% biomass, 1.1% geothermal and 0.4% biogas.

The outer ring represents the energy source distribution of the direct thermal energy consumption in the AMA combining the DHN and gas network and their twelve aggregated economic sectors: Agriculture, Mining, Manufacturing, Construction, Retail trade, Information, Financial, Real estate, Service activities, Public administration, Other service and Residential which are also listed in Table 2.3. Besides the buildings heated by the DHN the sectoral establishments and residential buildings assumed to be only heated via the natural gas network, by condensing boilers. Therefore, the share of natural gas increases to a proportion of 94.8%. The energy generated by the sources waste incineration, biomass, geothermal and biogas decrease to a share of 2.9, 1.3, 0.9 and 0.1 percent respectively. This reveals the high dependency on fossil fuels, and mainly, natural gas in AMA.

3.3 Energy flow analysis

The focus of this research lies on the extension of the DHN, i.e. the grid. The EFA helps to find the energy flows of the thermal energy supply. This section elaborates on the amount of direct energy inputs of energy carrier sources required for the thermal energy production within the AMA. In addition to the direct energy input, final energy use and losses, the developed EFA contains other accounting indicators to quantify the energy flows. These energy flows describe the energy streams in an urban area. Not all flows through urban areas given in Appendix A, composed by H. Haberl (2001, p. 14) are presented in the AMA. There is for example no export of energy sources within the metropolitan area. Therefore, the direct energy input is equal to the domestic energy consumption.

Not all primary energy imported to the metropolitan area is eventually used as final energy. The total primary energy input exists of hidden flows, import, domestic extraction and domestic hidden flows. Some energy used in the AMA is imported through pipelines transporting natural gas from Groningen. Some energy sources are shipped from Great Britain for the DHN. A total of 207.000 ton, equal to 0.75 PJ, of industrial waste is imported in 2015, which serves the Waste to Energy (WtE) power plants. (d. J. Swart, Pranger, and Kappelle, 2016, p. 29). In Purmerend and Lelystad domestic extraction takes place in the form of pruning waste in order to serve the biomass plants. As far as is known, no stocking of energy sources takes place.

The amount of useful final energy and the amount that is lost caused by conversion of the primary energy is computed for all municipalities and sectors. The contributions are computed by the equations 3.1, 3.2 and 3.3:

$$\dot{\mathbf{Q}}_{final} = \sum[(\dot{m}_{(final)} + \dot{V}_{n(final)})(H + H_g)] \tag{3.1}$$

$$\dot{\mathbf{Q}}_{losses} = \sum[(\dot{m}_{(losses)} + \dot{V}_{n(losses)})(H + H_g)] \tag{3.2}$$

$$\dot{\mathbf{Q}}_{direct} = \dot{\mathbf{Q}}_{final} + \dot{\mathbf{Q}}_{losses} \tag{3.3}$$

In these equations $\dot{Q}_{direct}$, $\dot{Q}_{final}$ and $\dot{Q}_{losses}$ are the conversions quantities of the flows of the direct energy input, final energy consumption and losses in Joules. The symbols $\dot{m}_{(final)}$ and $\dot{m}_{(losses)}$ are the masses of the solid fuels of the final energy consumption and losses in kg. The symbol units $\dot{V}_{n(final)}$ and $\dot{V}_{n(losses)}$ are the volumes of gas of the final energy consumption and losses in m^3 and H and H_g are the caloric values of the solid fuels and gases in J/kg and J/m^3.

3.3.1 Thermal energy supply by natural gas network

This section elaborates on the thermal energy consumption, supplied by the existing gas network. This gas network is connected to the high condensing gas boilers in the buildings. It is assumed that the gas used originates from gas fields in Groningen, and enters the AMA with the extensive gas network in the Netherlands. Of all energy flows entering the municipality, part of the direct energy input is lost caused by conversion. The amount of lost energy is determined by the efficiency factors of the condensing boilers.

In the Netherlands, 89% of the central heating boilers consist of high efficiency condensing boilers (Gerdes et al., 2016, p. 12). These boilers can reach a thermal efficiency higher than 90% (Che, Y. Liu, and Gao, 2004, p. 3264). Therefore, it is assumed that the overall thermal efficiency of the buildings heated by boilers in the AMA is 90%, this can be considered as undervalue considering the high efficiency of condensing boilers in the Netherlands, and common efficiencies which are often higher than 90% (Che, Y. Liu, and Gao, 2004, p. 3264).

The empirical data used to analyze the energy flows in the AMA is obtained from CBS (2017b). Figure 3.2 quantifies the contribution of the direct energy input per municipality excluding the thermal energy delivered by the DHN, it also shows the amount of useful final energy and the amount of energy that is lost caused by conversion of the primary energy.

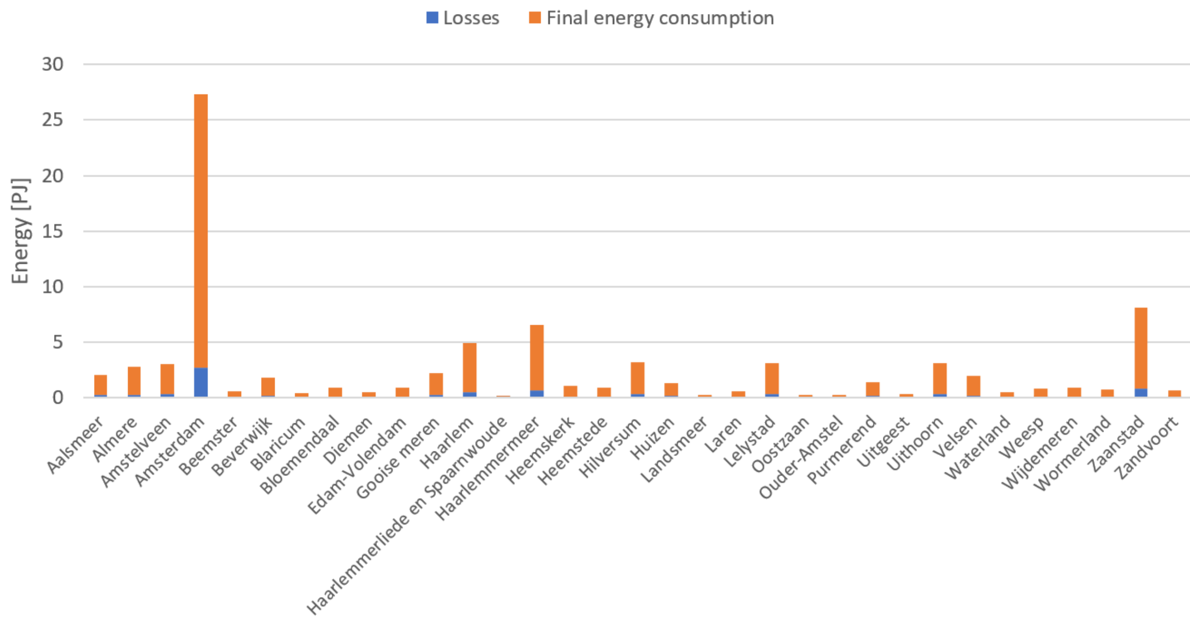

FIGURE 3.2: Total primary energy input and contribution of losses per municipality based on energy flow analysis (EFA). This graph discloses the final energy consumption and conversion losses excluding the district heat network.

The graphs indicate that most direct energy is consumed by the municipality of Amsterdam (27.3 PJ) followed by Zaanstad (8.1 PJ). The high-energy consumption of the municipality of Amsterdam can be explained because it accommodates approximately 39% of all sectoral and residential buildings. Both municipalities also score relatively high in the manufacturing sector due to the large number of companies within this particular branch. Amsterdam contains with 2560 establishments most companies active in this sector followed by Zaanstad with 730 establishments. The number of establishments per sector used for the EFA are obtained from CBS and listed in Appendix C. The Haarlemmermeer, which is the third most consuming sector within the AMA, scores the highest on agriculture, followed by retail, transport and storage. This can be explained by the presence of the Amsterdam airport.

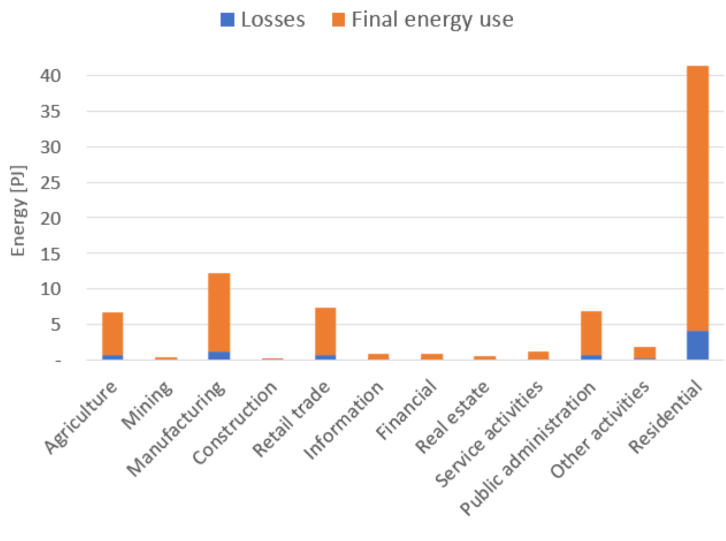

FIGURE 3.3: Total primary energy input and contribution of losses per sector based on energy flow analysis (EFA). This graph discloses the final energy consumption and conversion losses excluding the district heat network.

Analyzing the direct energy consumed within the economic sectors reveals the ascendancy of the residential sector (Figure 3.3.). This is caused by the large number of residential buildings compared to the sectoral establishments. 82% of all buildings in the metropolitan area of Amsterdam are residential buildings and together they consume 41.4 PJ of thermal energy. Another interesting result is that the agriculture sector mostly consists out of: Aalsmeer, Almere, Amstelveen, Haarlemmermeer and Uithoorn which together occupy 92.5% of the total consumption of this sector.

The direct energy input by the gas network reaches to an energy amount of 83.7 PJ. For the total final energy use of the AMA, combining all municipalities and sectors with each other, an amount of 75.3 PJ is reached. This energy is consumed within the buildings by boilers to deliver the heat required for space and tap water heating. The remaining 8.4 PJ is lost caused by conversion of the primary direct energy. The energy flows are visualized in a sankey diagram in Figure 3.4 below.

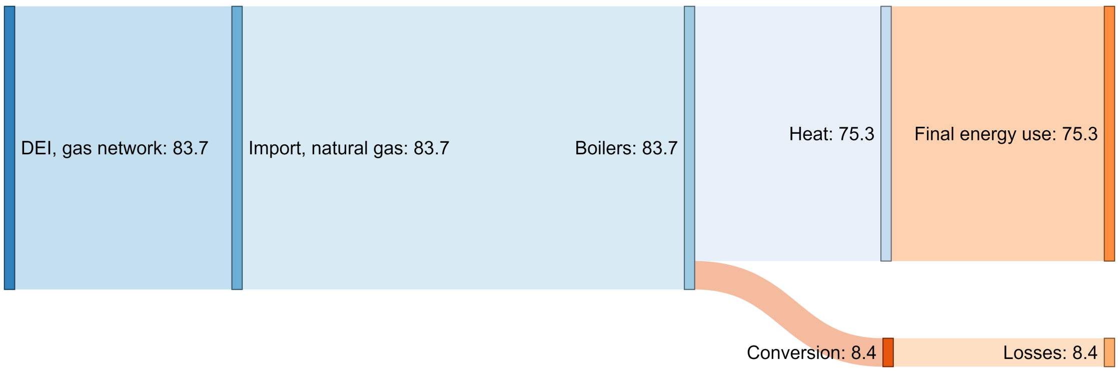

FIGURE 3.4: Sankey diagram of total primary energy input and flows in the gas network given in PJ. This diagram shows the direct energy input (DEI), imports, final energy use and losses based on energy flow analysis (EFA)

3.3.2 Thermal energy supply by district heat network

To expose the entire thermal energy use of the AMA the district heat network, DHN, also need to be analyzed with an energy flow analysis. Based on the distribution of the DHN in 2015 of the municipalities Almere, Amstelveen, Amsterdam, Diemen, Lelystad, Purmerend and Zandvoort it is obtained that approximately 120.100 buildings are connected to the DHN, covering approximately 11% of the AMA (CBS, 2017a). The direct energy input and energy losses of the thermal energy supply by the DHN depend mostly on the efficiencies of the combined heat and power (CHP) plants that deliver heat. The heat delivered by the power plants are obtained by the co-generation of both heat and electricity of the power plants, which makes the delivery of heat rather inefficient when the focus if fully on thermal energy. The reason why the thermal energy delivery is so inefficient can be explained by the biggest heat suppliers, located in Diemen:

The two biggest heat suppliers are the gas based power plants Diemen 33 and Diemen 34 which together serve respectively 13.9 PJ of thermal energy per year to the DHN of the municipalities of Almere, Amstelveen and Diemen (Menkveld et al., 2017, p. 39; Nuon, 2017b), the remaining heat is delivered to the district heat network of Amsterdam (Niessink and Rösler, 2015, p. 52). Next to the thermal energy, the power plants generate respectively 22.1 PJ electricity per year and have an efficiency of 50 and 55 percent (Endipedia, 2013; Nuon, 2017b; Verlinde, 2009, p. 34). Based on a standard calorific value of 31.65 GJ per 1000 m^3 this means that a total amount of 2.1 billon m^3 gas, with a potential energy of 68.0 PJ, is required to deliver 13.9 PJ of thermal energy by the Diemen 33 and 34 power plants. Hence, this means an efficiency of 20.4% (delivered energy/ potential energy), if the focus is on the delivery of thermal energy

The direct energy input and losses obtained from CHP plants are computed with the same equations as described in section 3.3 for all municipalities that are connected to the DHN. The thermal energy gained from the geothermal sources of Sanquin, NKI and Slotervaart hospital in Amsterdam are assumed to have minimal losses due to the lack of combustion. Electical energy used by the pumps to pump up hot water in the geothermal sources are left out of scope in the energy flow analysis. Also, the energy loss through the distribution pipes and electrical energy of pumps required to pump around the water in the network are left out of scope for the loss calculation of the EFA.

The final energy supply generated for the DHN is produced by eleven power generators located in eight different locations. The direct energy input of four of these power plants could be obtained from sources such as annual reports. Revealing the amount of energy consumed by the other power plants could be done by making assumptions and calculations based on known characteristics of for example their maximum capacities. Therefore, the unknown direct energy input of the remaining power plants are based on their maximum capacities (Mashhoodi, 2017). The required assumptions and calculations per power plant to determine the direct energy input are summarized below. The amount of energy produced and the municipalities connected per power plant are listed in Table 3.1.

Most final energy originates from natural gas, of which Diemen 33 and 34 have the biggest share. Diemen 33 has a maximum final electrical capacity of 8.4 PJ and thermal capacity of 5.7 PJ (Nuon, 2017b) with an efficiency of 50% (Endipedia, 2013). Diemen 34 has a maximum final electrical capacity of 13.7 PJ and thermal capacity of 8.2 PJ (Nuon, 2017b) with an efficiency of 55% (Verlinde, 2009, p. 34). Another gas based power plant connected to the DHN is the AMC with a maximum final electrical and thermal capacity of respectively 0.4 and 1.6 PJ (City of Amsterdam, 2017; AMC, 2013; M. Groot et al., 2008, p. 6). A smaller CHP in Zandvoort, which has a maximum final thermal capacity of 22 TJ (Niessink and Rösler, 2015, p. 69; Schepers and Valkengoed, 2009, p. 47). And a gas based power plant of the VU, which has consumed a given amount of 6.5 million m^3 natural gas in 2015 (Kesteren and Linden, 2016, p. 17). Based on a maximum electrical and thermal capacity of respectively 0.3 and 0.8 PJ (City of Amsterdam, 2017; TBI, 2017; M. Groot et al., 2008, p. 6) a thermal energy input of 0.1 PJ could be computed for the year 2015. The unknown efficiencies of the gas based CHP plants are all assumed to be 75%, based on similar CHP plants (P. Pilavachi, 2002, p. 2012) which can be considered as undervalue for a CHP plant.

In the AMA there is one waste incineration power plant operated by AEB Amsterdam. This waste to energy (WtE) plant consumes a given amount of 1.3 million ton household waste as direct energy input for the year 2015 (d. J. Swart, Pranger, and Kappelle, 2016, p. 9). This results in a final electrical and thermal capacity of 3.2 and 0.6 PJ for the year 2015 (d. J. Swart, Pranger, and Kappelle, 2016, p. 9). Based on the WtE (AEC) boiler, which reaches an efficiency of 71% in 2015, and the Waste Fired Power Plant (HRC) boiler, which reaches an efficiency of 94% in 2015, an overall efficiency of 81% is computed taking the different work loads into account (d. J. Swart, Pranger, and Kappelle, 2016, p. 31). Next to WtE, AEB Amsterdam also generates energy from biogas. The biogas is gained from sludge, that originates from sewage treatment installations. The total given biogas consumption in 2015 was 10 million m^3; this results into final energy capacities of 0.09 PJ for electrical and 0.08 PJ for thermal energy (d. J. Swart, Pranger, and Kappelle, 2016, p. 9). When using an assumed efficiency of 50% the caloric value of the biogas seems to be exactly the same as natural gas, see Appendix B. Therefore the efficiency of the biogas boiler is assumed to be 50% which can be considered as an undervalue.

Another supplier of thermal energy to the DHN is compassed by the combustion of organic matter in the biomass plants of Purmerend and Lelystad. The biggest biomass heating installation is located in Purmerend and is called de Purmer. This biomass plant retrieves its feedstock from the Dutch Forestry Service in the form of woodchips, gained from pruning waste of public owned forests. De Purmer annually consumes a given amount of 100.000 ton woodchips (Bioenergy 4 Business, 2016, p. 20) which equals to 0.8 PJ thermal, and 0.6 PJ electrical final energy (Menkveld et al., 2017, p. 47; Schepers and Valkengoed, 2009, p. 29). The second biomass heating installation is stationed in Lelystad. This installation produces, based on the maximum capacities, 0.2 PJ thermal and 0.05 PJ electrical final energy per year (Menkveld et al., 2017, p. 29; Nuon, 2017a). Based on similar biomass fueled CHP systems a efficiency of 75% is assumed (Dong, H. Liu, and Riffat, 2009, p. 10) which can be considered as an undervalue taking the co-generation of the biomass into account.

The energy delivered to the DHN by geothermal energy is served with two installations. The biggest installation is the geothermal system owned by NKI and the Slotervaart hospital. This installation reaches a final thermal capacity of 0.6 PJ (City of Amsterdam, 2017; IF Technology, 2013,

p. 12). The second geothermal system is located relatively close to the first installation and is owned by Sanquin. This installation reaches a final thermal capacity of 0.2 PJ (City of Amsterdam, 2017).

TABLE 3.1: Direct energy input per power plant

Power Plant	Cities connected	Connections	Direct energy input [PJ]
Diemen 33	Almere, Amstelveen, Amsterdam, Diemen	25.000	28.13*
Diemen 34	Almere, Amstelveen, Amsterdam, Diemen	50.000	39.85*
AMC	Amsterdam	7.500	2.61*
CHP Zandvoort	Zandvoort	600	0.03*
VU	Amsterdam	550	0.21
AEB Amsterdam (WtE)	Amsterdam	2.700	4.65
AEB Amsterdam (Biogas)	Amsterdam	370	0.32
de Purmer	Purmerend	24.900	1.80
Biomass Lelystad	Lelystad	5.100	0.33*
NKI/ Slotervaart hospital	Amsterdam	3.000	0.63
Sanquin	Amsterdam	1.100	0.24

** Direct energy input based on maximum capacities*

The direct energy input per power plant is listed in Table 3.1. The energy proportions are obtained based on the given fuel quantities and efficiencies of the individual power plants. Unfortunately, there are no accurate fuel consumptions available for some power plants. The amount of direct energy values of these power plants are computed based on the maximum capacities of the power plants, and are marked in the table with an asterisk symbol. These direct energy values are presumably lower than the given values. However, due to the lack of exact data, and in consultation with Mashhoodi (2017), the computed quantities are used for further calculations. The direct energy values of the power plants with no fuel consumption data will also be validated on their reliability in section 3.4.

The number of DHN connections are obtained from Nuon (2017b) and Niessink and Rösler (2015, p. 66-71). The number of households served per energy supplier connected to the DHN of Amsterdam are divided based on the final energy supply of the connected power plants and the DHN distribution rates retrieved from CBS (2017a). The total direct energy input, which is based on the losses and final energy supply reaches to 78.7 PJ in the year 2015; 18.1 PJ of thermal energy is delivered to the connected households as used final energy, which is a share of 23%. The rest of the energy can be considered as losses from a thermal energy perspective, and has a value of 60.7 PJ. However, not all energy is lost; 26.5 PJ is converted into useful, electrical energy.

Figure 3.5 quantifies the contribution of the direct energy input per municipality within the DHN. The graph also shows what amount is used as useful, final energy and what amount is lost due conversion of the primary energy. In this graph only the connected municipalities contain an energy input, the remaining municipalities do not have a DHN connection and are therefore considered to have a zero energy input for the DHN. The direct energy input of the Diemen 33 and 34 distributes their thermal energy among four different municipalities. Therefore, this energy is equally distributed among these municipalities, based on the amount of connected households in the urban areas. The graph reveals that most energy delivered by the DHN is destined for Almere. This city also contains the most connected buildings in the AMA. Another interesting result is that although Almere only has twice the number of connected buildings compared to Purmerend, it imports more than 20 times the amount of direct energy. This could indicate that the amount of thermal energy produced by de Purmer in Purmerend is better adjusted to the heat required in this area, compared to the thermal energy produced by Diemen 33 and 34.

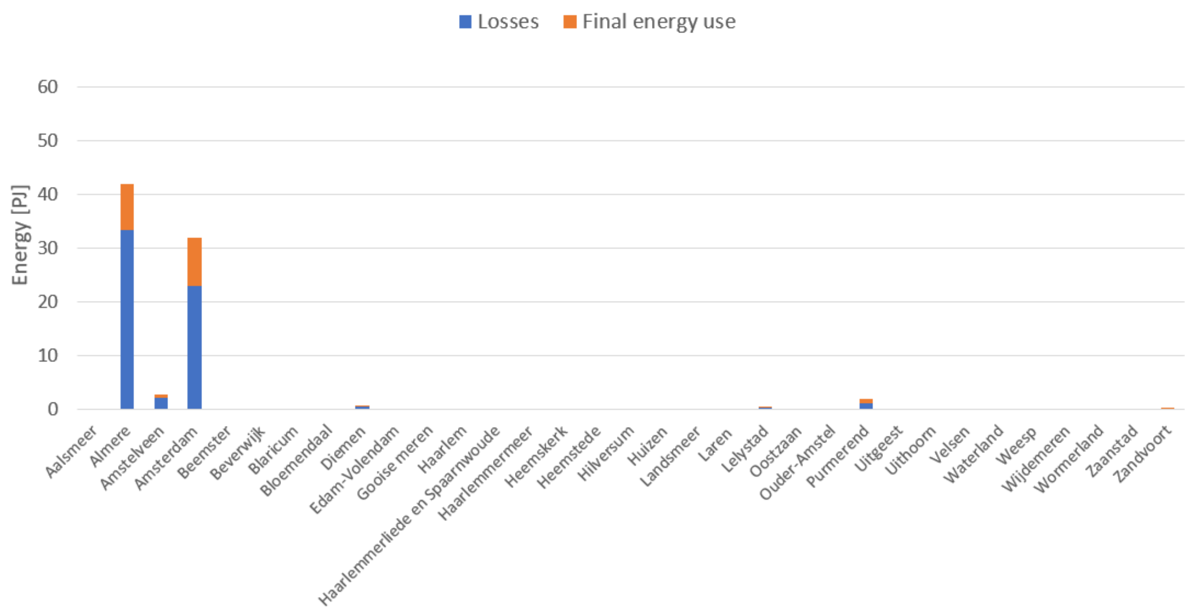

FIGURE 3.5: Total primary energy input and contribution of losses per municipality of the DHN, based on energy flow analysis (EFA)

No graph is shown for aggregated sectors because no information is available for the type of sectors the DHN is connected to. To visualize the energy streams a sankey diagram is made which outline the different energy flows of the DHN (Figure 3.6). All thermal energy delivering power plants and their heat production quantities are shown in this diagram.

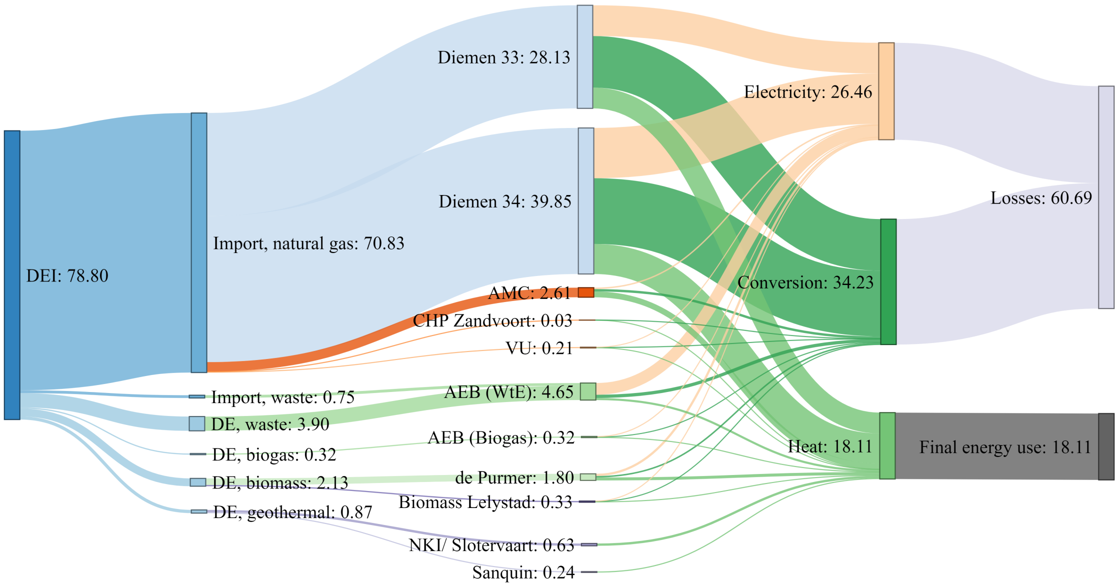

FIGURE 3.6: Sankey diagram of total primary energy input and flows in the DHN given in PJ. This diagram shows the direct energy input (DEI), imports, domestic extraction (DE), final energy use and losses based on energy flow analysis (EFA)

3.3.3 Combining the gas network and district heat network

The total amount of energy consumed in the entire metropolitan area is determined by combining the two heat suppling methods. By doing so a complete energy consumption profile of the AMA is made. Adding the two energy suppling methods gives a sum of 162.5 PJ direct energy input. This amount of primary energy is needed to generate enough thermal energy required by all municipalities. Of the total direct energy input 93.4 PJ could be converted to useful, final thermal energy. The remaining 69.1 PJ is lost caused by conversion and electricity production.

Figure 3.7 is based on the combined data of the gas delivered by the gas network and the energy delivered by the DHN. The graph reveals that the direct energy input of Amsterdam increased to 59.3 PJ. Also, the direct energy used by Almere is approximately 16 times larger than the district heating network. Both cities receive a significant amount of heat from the Diemen CHP plants. Due to the high inefficiencies based on generating thermal heat by the power plants high energy losses occur. In this way the energy consumption in Almere, which has many of its households connected to the DHN, is approximately ten times larger than Haarlem, with nearly the same number of residents.

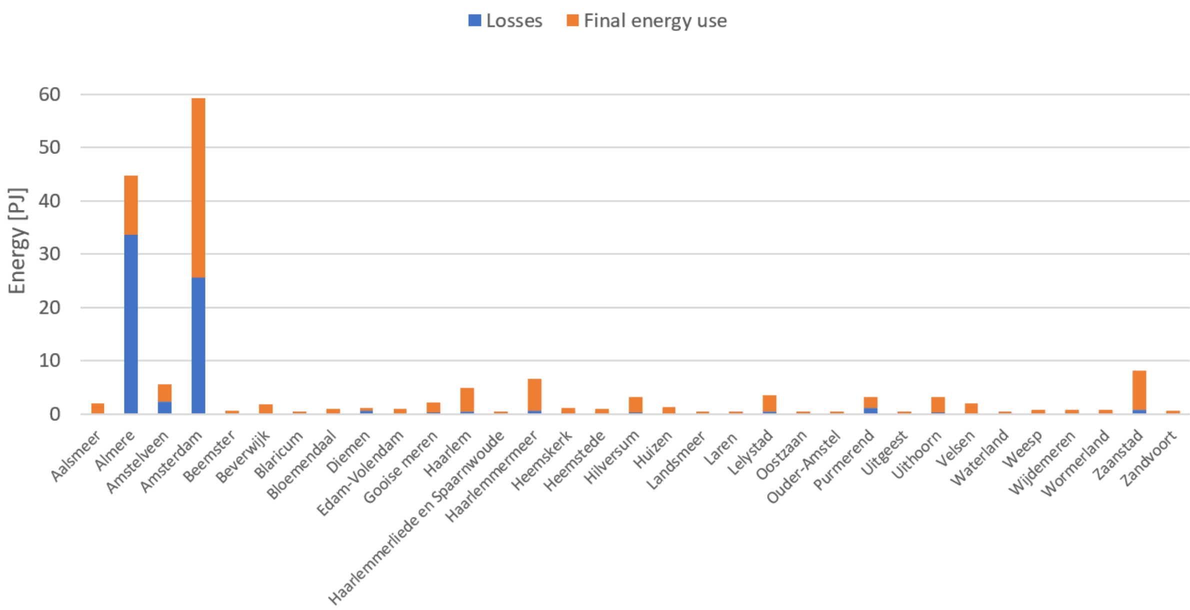

FIGURE 3.7: Total primary energy input and contribution of losses per municipality with DHN included, based on energy flow analysis (EFA)

The direct energy consumed by the economic sectors based on the energy flow of AMA can be seen in Figure 3.8. This graph discloses the complete final energy consumption and conversion losses. Due to data unavailability data on the type of buildings that the DHN is connected to, and due to the fact that mostly residential buildings are connected to the DHN (Niessink and Rösler, 2015, p. 19), it is assumed that all energy delivered by the DHN is consumed within the residential sector. This results in a high consumption amount by the residential sector, which increases to a spacious 120 PJ. This is almost 74% of the total direct energy input of the AMA.

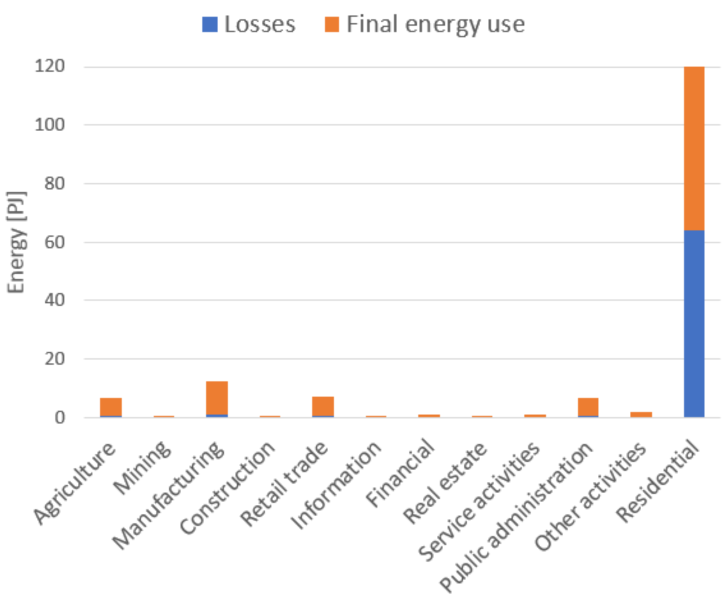

FIGURE 3.8: Total primary energy input and contribution of losses per sector including DHN, based on energy flow analysis (EFA)

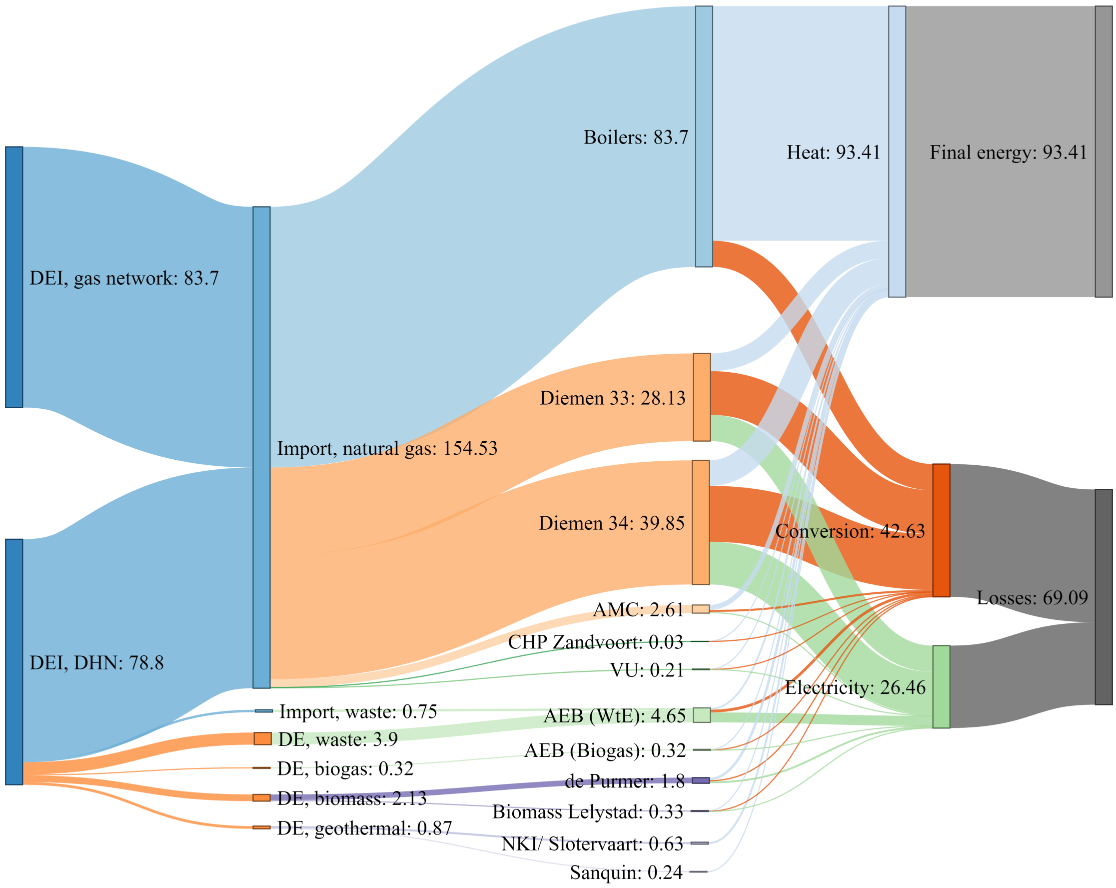

FIGURE 3.9: Sankey diagram of total primary energy input and flows of the gas network and DHN combined, given in PJ. This diagram shows the direct energy input (DEI), imports, domestic extraction (DE), final energy use and losses based on energy flow analysis (EFA)

3.4 Annual heat consumption per consumer and data validation

In the design process of a district network it is valuable information to know the average annual consumption per building. The total thermal energy consumption, supplied by both the DHN and the high condensing gas boilers, equals 93,4 PJ. The annual consumption differs a lot per municipality and sector, and is based on the final energy consumption. The final energy consumption is the energy required by the households to heat the water needed for tap water and space heating. With a total amount of nearly 1.4 million buildings it means that an average annual consumption of 68.8 GJ per year per household is reached.

This lies within the Dutch functional space heating demand and is a validation for the used data. The demand varies however per building-type and construction year. The annual heat demand can be as high as 95 GJ per year for a detached houses build before 1940, to 6 GJ per year for an apartment of at least 4 stories high, if build after 2010 (Folkert and Wijngaart, 2012, p. 50). However, the average annual heat demand in the Netherlands is only 34 GJ per year, which means that the consumption in the AMA is significantly higher than the Dutch average (Miltenburg, 2016, p. 15).

As mentioned, the annual consumption varies a lot per municipality and sector. Therefore, the annual final consumption rates are aggregated for all municipalities and sectors in the AMA given in Appendix C; Table C.3. The different annual consumption values for all municipalities within the AMA with the DHN included can be found in Table C.4. Noticeable differences on the average annual consumption can be obtained between the two tables. The tables, including the DHN, show higher average energy consumption rates within the municipalities. Especially when the final energy values of the residential sector in Almere are compared, then expressive disseminations are obtained. In both tables an equal number of 78.974 households is used to compute the average final energy consumption. The final energy consumption in Almere is 13.9 GJ per year when excluding the DHN and 122.2 GJ per year when the DHN is included. The low final energy value of 13.9 GJ per household, in the excluding DHN situation, can be explained because a considerable number of the households is connected to the network in Almere. The high final energy value of 122.2 GJ per household for the consumption including the DHN reveals that to much thermal energy is produced by the Diemen 33 and 34 power plants, which are the only heat suppliers to the DHN of Almere. When computing the potential thermal energy delivered to Almere by Diemen 33 and 34 when assuming an operating factor of 81%, which is the average operation duration per year according to Verlinde (2009, p. 34), the final energy consumption of Almere would become 101.6 GJ per year per household. This is still nearly three times higher than the Dutch average of 34 GJ per year. This means that it is likely that the Diemen 33 and 34 power plant do not supply all there thermal energy to the DHN, and have the capacity to extend their heat network.

Although there is enough heat available by the Diemen 33 and 34 power plant to extent the network, Almere, and especially the green city district project developed by the world heritage exhibition of Floriade 2022, do not want to connect their buildings to the existing network. This because, they wan to avoid a lock-in of the unsustainable power plants (Timmeren, 2017). Therefore, it is important to develop sustainable solutions to foresee the required heat within the AMA.

3.5 Energy flow analysis conclusion

The goal of this chapter is to gain information about the energy flows within the AMA. With this information the first sub-question given in section 1.4 can be answered, stated as follows:

What is the final thermal energy consumption in the Amsterdam metropolitan area and its economic sectors and household use?

To answer the first research sub-question empirical data is analyzed with an energy flow analysis (EFA). The EFA gives insight in how much thermal energy is consumed in the specific sectors and municipalities of the AMA. Sectors analyzed are; agriculture, mining, manufacturing, construction, retail trade, information, financial, real estate, service activities, public administration, other service and residential sector.

In this chapter the analysis is split up in two suppling processes, the thermal energy supplied by; natural gas networks and the DHN. First the supply by the gas network, delivering natural gas to the high efficiency condensing boilers, is elaborated. According to the analysis it turns out that the municipality of Amsterdam is by far the most consuming area in the AMA, followed by Zaanstad. This can be explained because it covers a significant share of all sectoral and residential buildings, approximately 39%. Most consuming sector within the AMA is the residential sector, followed by manufacturing. Although the amount of energy used per building is not sufficiently high in the residential sector, the large quantities relating to the other sectors ensures a high overall energy use. All sectors and municipalities combined results in a total direct energy input of 83.7 PJ. 75.3 PJ of the total direct energy input could be used as useful final energy. The remaining is lost by convection.

Secondly, the supply by the DHN is analyzed. Some municipalities contain households connected to a DHN. Of these municipalities, Almere and Amsterdam received the most thermal energy. It is unknown what amount is supplied to the different sectors. Therefore, it is assumed that all thermal energy delivered by the DHN is consumed by the residential sector. The heat in the DHN originates from five contributing energy carriers; natural gas, industrial waste, biomass, biogas and geothermal energy. It could be concluded that, of all energy carriers used, natural gas is dominating. This energy carrier outnumbers the remaining energy sources significantly. The reason for this is caused by the large thermal energy share of the Diemen 33 and 34 power plants. An interesting finding is that especially Diemen 33 and 34 produce more heat than can be delivered to the DHN. Also when the amount of thermal energy produced is adjusted with a limited operating time, 3 times of the Dutch average heat consumption is produced. Therefore, it can be concluded that not all thermal energy produced is delivered to the connected households. Furthermore, there is enough heat by Diemen 33 and 34 to expand the current DHN. From the total direct energy inputs of the DHN, a relatively small amount ends up as useful final energy. This mainly occurs due to the co-generation of the power plants. All combustion processes combined results in a total direct energy input of 78.7PJ. 18.1 PJ of this direct energy input could be used as useful final energy. The remaining 60.7 PJ is considered as lost.

Combining the results of the gas network and the district heat network gives the answer for the first sub-question. Adding both supply processes results in a direct energy input of 162.5 PJ. The final energy use reaches to 93.4 PJ. The rest is considered as loss from a thermal energy perspective. The municipalities Amsterdam, Almere and Zaanstad receive most energy. The residential sector is the most consuming sector. However, the outcomes relating to the different sectors are considered to be not accurate enough. Therefore, analysis on the different sectors is not executed in the following chapters. The energy flow quantities obtained with the EFA are further used for the analysis in the next chapters.

Chapter 4

Impact assessment and visualization

4.1 EFA-LCA impact approach

The environmental impact of the thermal energy consumption in the AMA is based on the performed EFA analysis to determine the direct energy input. Because the direct energy input is measured with a mass indicator the aligning impact per unit of mass can easily be obtained. In this way the consumption can be transformed to the environmental impact, e.g. the global warming potential per cubic meter of natural gas consumed.

LCA is an extensive tool to use because of the wide considerations it comprehends. It considers the entire life cycle of a product or process and quantifies the correlated impact. Also, the assessment can be performed based on different impact categories. The combination of an EFA and LCA is not broadly used. However, a combined Material Flow Analysis (MFA) and LCA study is widely employed in the field of industrial ecology (Silva et al., 2015, p. 157; Rochat et al., 2013, p. 642; Venkatesh, Hammervold, and Brattebø, 2009, p. 533). Because of the similarities between EFA and MFA, which both contain a mass based indicator, it is suitable to perform a combined EFA-LCA approach.

Using a LCA approach actually means that existing LCA studies are used to approximate the emissions emitted in the AMA. In other words, no new LCAs will be assessed for the power plants located in the case study area. The LCA studies used are coming from a comprehensive LCA inventory database. However, despite the accuracy of existing LCAs, using LCAs of comparable technological processes can introduce uncertainties and shortcomings, e.g. internal proceedings and used efficiencies of the selected processes could differ compared to the processes in the case study area. Therefore, the results should be exercised with great caution.

Combining both tools results in multiple impact categories which can be used to determine key performance indicators (KPI). The KPIs will be used to analyze the current environmental performance of the metropolitan area. Adding an impact based KPI will increase the environmental information and will therefore be higher in value (Voet, Oers, and Nikolic, 2004, p. 7).

4.2 Assessing Impact

The assessment of the impact is conceived for the different processes that generate thermal energy in the AMA. The processes that are selected for the impact assessment are:

- Natural gas Production
- Natural gas combustion in CHP
- Natural gas combustion in boilers
- Waste incineration
- Biomass combustion in CHP
- Biogas combustion in CHP
- Geothermal Energy production

The relating environmental impact of the processes will be composed and selected with Simapro 8.1 software. This program uses the latest LCA inventory database, Ecoinvent 3.1 (PRé Consultants, 2016, p. 3). The selected LCA process will altogether encompass the extraction of raw abiotic resources until the combustion, were the resources are disposed as emissions with heat as end product. The overall impact of the processes will be computed based on the total direct energy input, as given in the EFA per process. The results will also be computed per unit of volume (m^3) for the natural gas production, and per unit of energy (MJ) for the remaining processes. In this way the contribution of each process can be given as a percentage of the total impact.

For each selected process with its corresponding environmental impacts, similar LCA studies are often available in the Ecoinvent database. The best suited LCA studies related to these processes in the AMA are selected based on the characteristics of the available processes in the Ecoinvent database. All selected processes will be assessed on matching raw materials, combustion/production methods, capacities, location and material supply. However, the model of these selected processes is never an exact representation of the current situation in the AMA. This means that there will always consist an uncertainty on used parameters of used resources, geographical boundaries and time frames. Notwithstanding the uncertainties, the selected processes will disclose valuable information on the environmental performances of the processes and the metropolitan area.

The processes will be selected based on their initial purposes. This means that the selection of a process that describes a CHP plant with both electricity and heat as output, will be based on the intended purpose of the plant. The intended purpose of the Diemen power plant is electricity generation. The waste heat produced by this power plant is later used as byproduct. Therefore, the process selected relating to the Diemen power plant is based on a natural gas fired power plant with electricity as output and heat as emission. The environmental impact of the heat production ie determined using allocation factors. Allocation splits the in- and/ or outputs of a process and assigns the part of the associated impact that is responsible for the energy flow. Allocation can be performed on different specifications, all resulting in different outcomes. The type of allocation used in this study is based on the economic value. This method requires the price of both electricity and heat. The prices used to determine the environmental impact of the thermal energy produced are based on the prices that individuals have to pay for the different energy types. According to Wat kost een kilowatt stroom (2017) the price of electricity, based on an one year contract at Nuon, is 0.206 €/kWh, equaling 57.22 €/GJ. According to Nuon (2017c) the price of heat, delivered by DHN is 22.26 €/GJ. This results in the allocation factors of 72% responsible caused by electricity and 28% responsible due thermal energy.

The selections are made on the thermal energy producing processes and can be found in table 4.1.

TABLE 4.1: Processes selected form the Ecoinvent 3.1 database

Process	**Selected LCA**	**Geographical boundaries**	**Process description and selection accountability**
Natural gas Production	Natural Gas, at production onshore	Netherlands	First, the natural gas consumption by the households with boilers and the gas combusted in the power plants has to be mined. The ecoinvent alternative process selected describes the: "exploration and production of oil and gas on the Groningen and inland fields (onshore). Data doesn't include combusted fuels for turbines, motors etc. It includes only testing (fuel requirements and emissions)." The data is based on collected environmental NAM reports. This process is therefore the closest to reality.

Continued on next page

Table 4.1 – continued from previous page

Process	Selected LCA	Geographical boundaries	Process description and selection accountability
Natural gas combustion in CHP	Natural gas, burned in power plant	Netherlands	Represents the natural gas based power plants within the AMA, which are the Diemen 33 & 34, AMC, VU and Zandvoort CHP plants. The ecoinvent alternative selected includes the: "fuel input from high pressure (NL) network, infrastructure, emissions to air, and substances needed for operation." The used technology is based on the average of the installed power plants. This alternative approaches the different CHP plants in the AMA and is therefore selected.
Natural gas combustion in boilers	Natural gas, at boiler atm. low-NOx condensing non-modulating <100kW	Switzerland	The boilers within the AMA are high efficiency boilers. The alternative process selected which is comparable to the case of AMA includes the: "fuel input from low pressure (CH) network, infrastructure (boiler), emissions to air and water, and electricity needed for operation." The technology used in this LCA study relies on the available technology of the mid 90s.
Waste incineration	Heat, for reuse in municipal waste incineration only, treatment of municipal solid waste	Netherlands	This process represents the AEB WtE power plant. The selected dataset describes the activity of waste disposal of municipal solid waste in a municipal solid waste incinerator. The process includes: "waste incineration from waste reception gate and delivery into waste bunker at incinerator plant site (without transports to the incinerator) & Waste-specific short-term emissions to water from leachate. Long-term emissions from landfill to ground water." The technologies are based on average Swiss waste incineration plants and are representative for modern plants used in Europe.
Biomass combustion in CHP	Heat, central or small-scale, other than natural gas heat production, mixed logs, at furnace 30kW	Rest of the world (RoW)	The most relating process that describes the combustion of pruning forest waste of the biomass plants located in Purmerend and Lelystad is the process which describes the combustion of wood logs in a Swiss furnace installed in 2014. This process is globally used as a first approximation. The ecoinvent process includes: "the combustion of natural wood logs in a modern boiler. Included are the infrastructure, the wood requirements, the emissions to air, the electricity needed for operation, and the disposal of the ashes." The capacity range is 10-50 MW covering both biomass plants in the AMA.
Biogas combustion in CHP	Heat, at cogen with biogas engine , agricultural covered	Switzerland	Process describing the biogas combustion is conducted by Jungbluth et al. (2007, p. 184-196) by use of biogas in a co-generation unit. Included processes are: "emissions to air, biogas consumption, use and disposal of operational supplements as well as infrastructure expenditures." The output of this process is, agriculture covered with biogas engine and delivers the co-products: "heat and electricity, at cogen with biogas engine, agricultural covered". The degrees of efficiency are as follows: electricity: 33% and heat: 67%.

Continued on next page

Table 4.1 – continued from previous page

Process	Selected LCA	Geographical boundaries	Process description and selection accountability
Geothermal Energy production	Electricity, high voltage electricity production, geothermal	Rest of the World (RoW)	A general form of geothermal electricity generation for the modeling of geothermal energy is used. No exact technology match could be found, the best fitting solution therefore describes the generation of high voltage electricity. The selected process is modeled based on a binary cycle plant which has an average capacity of 5MW. The process includes: "all operation and maintenance activities and materials of the power plants. The loss of the working medium is included. This dataset includes cooling water, but no cooling infrastructure"

Based on the selections, the associated environmental impact of the thermal energy suppliers in the AMA can be simulated. After the impact is computed the formatted allocation factor is applied. This results in the impact distribution which can be seen in the stacked columns on the next page. Figure 4.1 gives the distribution per MJ and figure 4.2 represents the total emissions and distribution, based on the direct energy input results obtained from the EFA in chapter 3. The impact categories composed are based on the CML 2 baseline 2000 method, which uses the reference situation normalization of the Netherlands in the year 1997, explained in subsection 2.1.2.

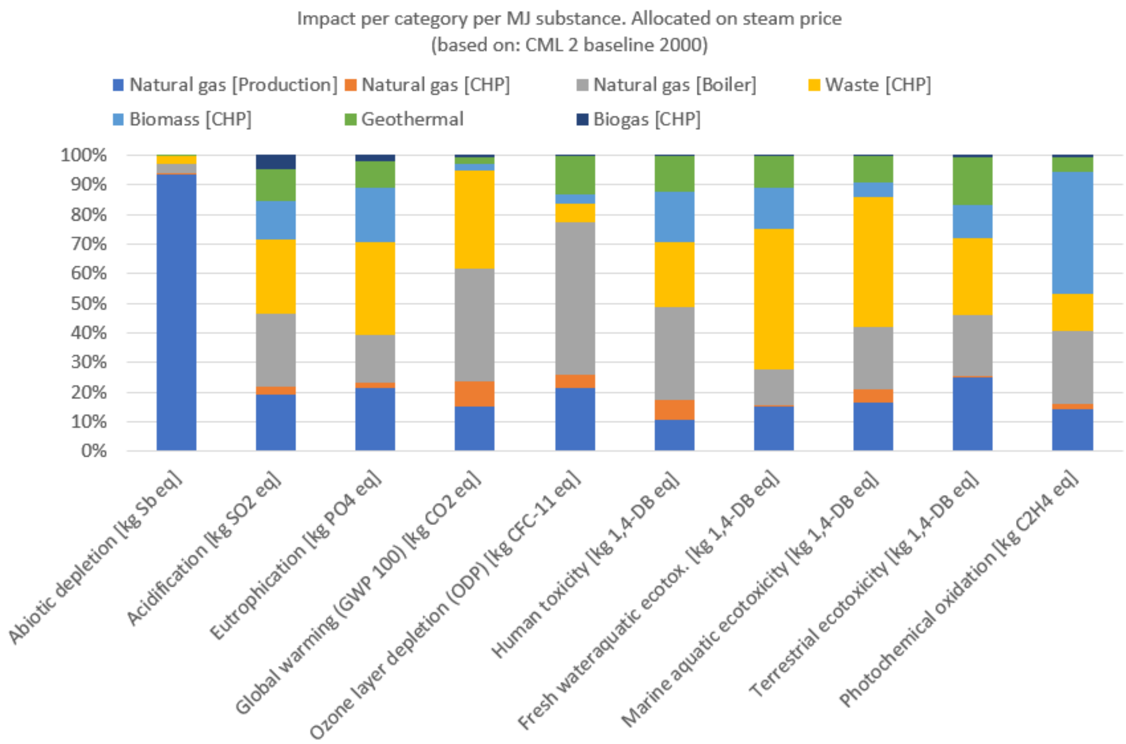

FIGURE 4.1: Impact per category per MJ substance. Allocated on steam price. (based on: CML 2 baseline 2000)

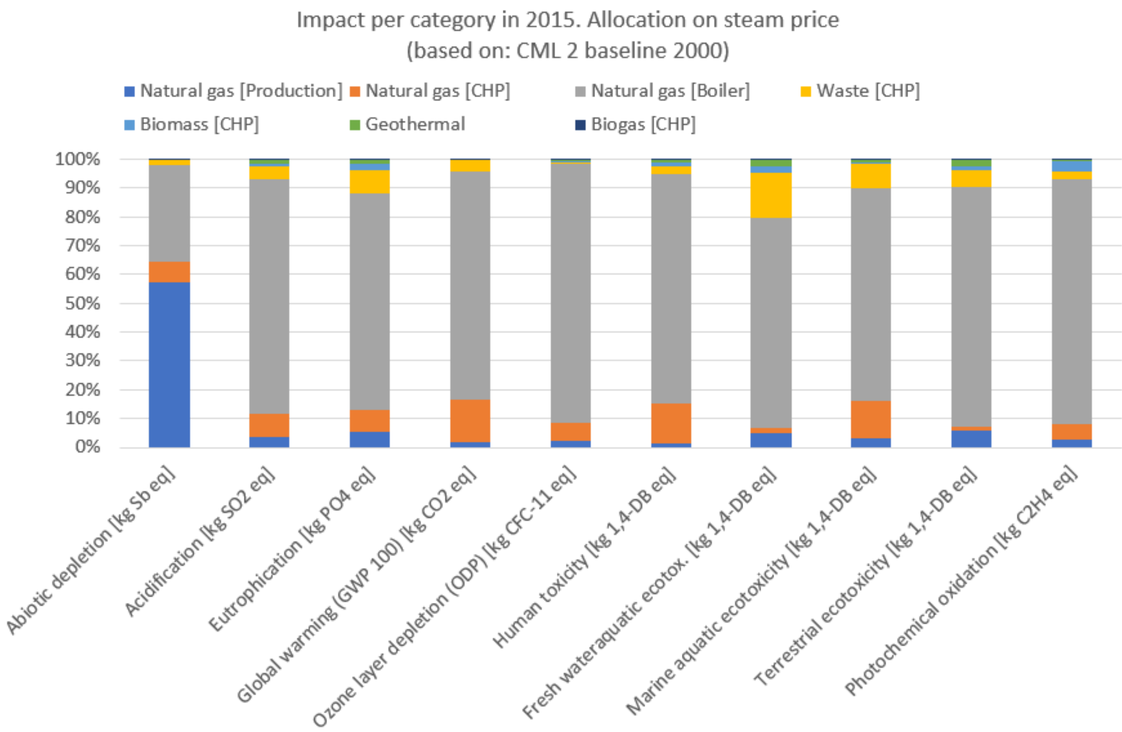

FIGURE 4.2: Impact per category based on data of 2015, obtained by EFA. Allocated on steam price. (based on: CML 2 baseline 2000)

Analyzing the distributions of the emissions per MJ on all impact categories, it can be obtained that the natural gas production is almost fully responsible for the abiotic depletion impact category. This is an obvious result because the production of natural gas is mostly dedicated to the extraction of natural gas. In the remaining impact categories, especially waste incineration and natural gas combustion by boilers are dominating. These two combustion methods emit overall the most, considering CO_2, the main chemical compound of the global warming impact category. An other notable finding is the ascendancy of biomass in the photochemical oxidation impact category. This means that using more heat generation by biomass could lead to more smog. When analyzing the emissions per MJ, it should be noted that the emissions belonging to the natural gas boilers are not allocated. The reason for this is that this technology does not contains co-generation of both thermal and electrical energy. The remaining generation technologies all contain co-generation techniques, and are therefore adjusted with the aforementioned allocation factor.

Focusing on the emission distribution of all impact categories with the total direct energy input retrieved from the EFA, the domination of the emissions by the natural gas boilers stand out. The reason for this is that a significant amount of direct energy is used by the condensing boilers in the AMA. Other large direct energy consumers in the AMA originate from the combustion of natural gas. Compared to the high efficiency of condensing boilers the combined heat and power plants incinerating natural gas emit much less emissions. Therefore, the heat production by natural gas power plants is emitting less GHG than the condensing boilers. Corresponding to the distribution per MJ the production of natural gas also dominates the abiotic depletion in the total emissions.

4.3 Conducting baseline

To be able to compare the environmental performance of different thermal energy supply configurations a baseline of the year 2015 is composed. This baseline will exist of a sum of the KPI impact categories obtained by the LCA impact assessment. With the exact KPI impact values it is possible to examine if environmental improvements are made. However, not all ten impact categories are used. Since climate change, with the relating CO_2 emissions, a better air quality and decreasing the dependency of fossil fuels are high on the agenda of the AMA (Choho, 2015, p. 7; Choho, 2016, p. 5).

Therefore, relating impact categories are selected as KPIs. The KPIs are used to evaluate the current impact profiles of technologies. This is performed by comparing the total mass of the unit substance equivalents with those of the proposed improvements. In this way the amount of improvement of the environmental profiles can be given as a percentage, relative to the baseline year 2015. Table 4.2 represents the selected KPIs and belonging mass [kg] based on the thermal energy suppliers in the year 2015.

TABLE 4.2: KPI impact categories performance

KPI	Mass [x1.000.000]	Unit
Abiotic depletion	152.35	kg Sb eq
Acidification	7.64	kg SO_2 eq
Global warming (GWP 100)	7870.54	kg CO_2 eq
Photochemical oxidation	0.86	kg C_2H_4 eq

These values are used to compare the total mass [kg] of the proposed improvements, given in chapter 5. All impact categories and the contribution among the different processes can be found in Appendix D.

4.3.1 Validation of results

The results are analyzed to validate the conclusions obtained from the LCA impact assessment. This is done by comparing the outcomes of relating studies performed on the environmental performance of the DHN and the Dutch natural gas consumptions. In most relating studies, only the environmental performance of the thermal energy supply systems is assessed based on the CO_2 emissions. Therefore, only the results of the CO_2 levels can be compared. The results are often given in kg CO_2 per GJ. These studies show that a DHN in the Netherlands emit around 20 kg CO_2 per GJ. However, more comprehensive methods reveal higher emission values, which are around 29.81 kg/GJ to 34.81 kg/GJ during peak hour (Miltenburg, 2016, p. 13). Considering the results obtained from the impact assessment a value of 75.3 kg CO_2 per GJ is computed for the combustion of natural gas by boilers. The amount of CO_2 emitted by the DHN attains after allocation the value of 19.9 kg/GJ. The combined average emissions of the total thermal energy supply equal 48.5 kg/GJ. This means that the results retrieved by the impact assessment are comparable with the outcomes of other relating studies.

4.4 Spatial impact analysis

Knowing where all emissions are emitted is of high importance. Eventually, all emissions will end up in the atmosphere. However, the diffusion process of the different emissions requires some time. This results in a high concentration of unnatural aerosols which affect the reflection of incoming solar lights, absorbs solar radiation and has additional affects on water vapor and cloud formation. This may result in extreme weather events with more, and extreme rainfall and smog (Russchenberg et al., 2005, p. 2252). Therefore, the emissions emitted in urban areas have higher effects on the local climate than emissions emitted elsewhere.

The emissions emitted by the households living in the AMA and the power plants connected to the DHN are transmitted within the boundaries of the AMA. The emissions related to the natural gas production are in this study assumed to be emitted at the Groningen gas-fields. The emissions produced by the power plants are released in the atmosphere with higher concentrations. Emissions produced by the households with the home gas boilers are more spread out over the entire metropolitan area.

In order to visualize what the geographical characteristics of the emissions are, geographical bounded data of the energy carriers consumed is required. Finding the locations of the power plants connected to the DHN could be performed by hand. Due to the large number of residential buildings and establishments within the twelve investigated sectors, external data is used. Because all buildings are either heated by district heating or by natural gas, geographical bounded empirical data on the gas consumption is necessary. The requisite data could be obtained from the two network operators in the AMA, Alliander and Stedin. The data obtained from Liander (2017), which covers the largest part of the AMA, gives the gas consumption of the small end users of all residential buildings including smaller company establishments which consume less than 40m^3/hour. The data is presented on aggregated postcode level to guarantee the privacy of the end users. Data obtained form Stedin (2017) is structured in a similar manner. Stedin supplies a smaller share in the AMA than Alliander. A map with the network coverage is added in Appendix E to exemplify the total coverage per network operator. The data of both Alliander and Stedin is filtered on the cities and towns within the AMA to ensure that only end users within these boundaries are used. The cities and towns used to filter the data can as well be seen in Appendix E. Because the data file used does not contain the high consuming end users (over 40m^3/h) a difference between the computed direct energy input, retrieved with the EFA, and the direct energy input of the data from Alliander and Stedin occur. Where the EFA accorded an energy input of 83.7 PJ the energy input of Alliander and Stedin reaches 53.6 PJ. This amount is responsible for households and small and medium-sized enterprise gas users, using a gas amount less than 40m^3/h. The remainder 20.1 PJ is responsible for the large-scale consumers, which are due to the lack of data not included in the spatial impact analysis within this study.

For the visualizations of the emitted emissions, the outcomes retrieved from the LCA impact assessment on the selected KPI impact categories are used. The visualization method, applied with QGIS, is an inverse distance weighting (IDW) interpolation. The cell-size X and Y which is the size of each pixel of the output raster was for both X and Y set on 75. The results can be seen in the Figures 4.3, 4.4, 4.5 and 4.6.

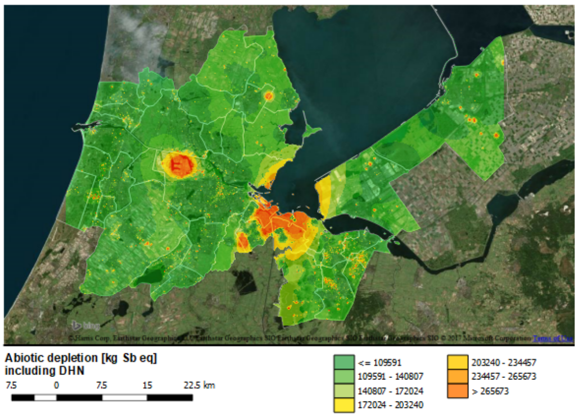

FIGURE 4.3: Abiotic depletion

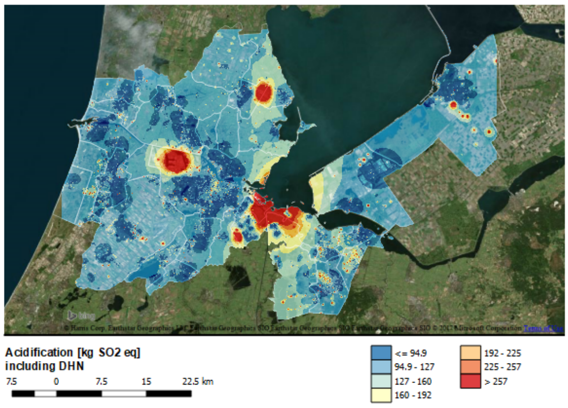

FIGURE 4.4: Acidification

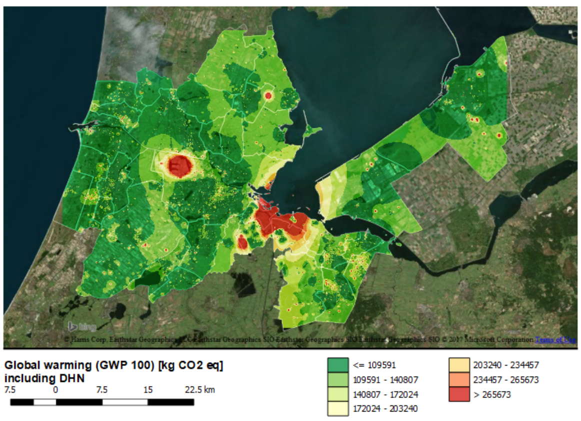

FIGURE 4.5: Global Warming (GWP 100)

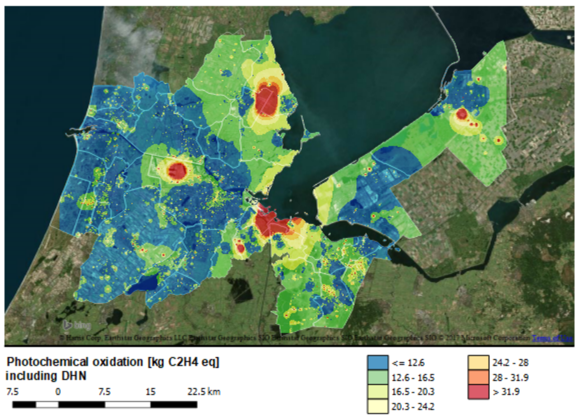

FIGURE 4.6: Photochemical oxidation

As can be obtained from the graphs, especially the power plants emit a high concentration of emissions within the metropolis. Therefore, urban areas close to the power plants will face significant more effects on the local climate and smog. When analyzing the graphs separately it can be seen that the Diemen power plants are strongly represented in every graph. The biomass plants located in Lelystad and Purmerend scores relatively low on the global warming relating to the other KPIs. However, on the photochemical oxidation category it is one of the most polluting processes, which contributes to summer smog. The waste incineration power plant scores relatively high on the acidification category and therefore contributes to negative consequences such as acid rain.

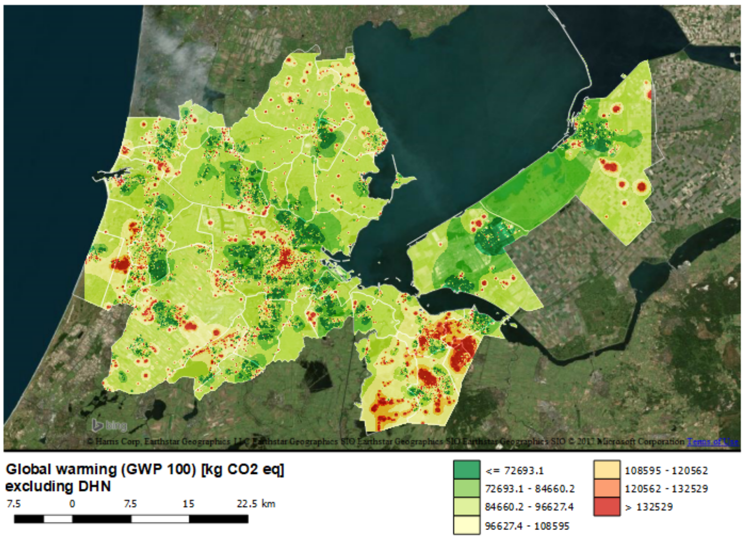

FIGURE 4.7: Global warming (GWP 100) of small end users based on data obtained from Alliander and Stedin, excluding the district heat network

To display the most consuming households within the AMA an interpolation is also made on the data retrieved from Alliander and Stedin, excluding the emissions emitted by the power plants (Figure 4.7). This graph shows mainly a high consumption in the municipalities Blaricum, Bloemendaal and Hilversum. As can be obtained from CBS (2017d) the average house size in this areas is larger and are often detached from each other. More gas is consumed to heat larger spaces. This could be explained by the fact that detached houses require more heat than, for example, row houses and apartments. Apart from the type of the houses, also the the age of the buildings plays a major role (Folkert and Wijngaart, 2012, p. 50). This can be derived by the high consumptions within the city center of Amsterdam. Which could besides, also represents high consumptions values due to the high population concentrations within this area.

4.5 Impact assessment and visualization conclusion

This chapter aims to give insight into the sustainability of the current technologies used to supply heat. No subquestion will be answered. However, this chapter gives valuable information on the environmental profile of the AMA, and creates a baseline which represents the environmental impact of the year 2015. This baseline will subsequently be used in chapter five to answer subquestion 2.

From the energy flows obtained it was possible to perform an impact assessment. With an impact assessment the thermal energy generation processes can be assessed on their environmental performance and exposes which process contributes to the highest emissions. This gives insight in the most polluting heat generation processes. The results based on the average emissions per MJ of the simulated processes, reveal that waste incineration and natural gas combustion in high efficiency condensing boilers contributes most to the emission distribution in most impact categories. The results on the total emissions, based on the direct energy input, reveal that the production of natural gas contributes the most to the abiotic depletion category. In the remaining impact categories the process that simulate the combustion of natural gas in high efficiency condensing boilers stands out relative to the remaining processes. This process mainly scores high in the acidification, global warming, ozone layer depletion and photochemical oxidation impact categories.

With a spatial analysis the locations emitting most emissions are identified. The analysis revealed that, high emission concentrations occurs close to the power plants. Therefore, urban areas located near power plants will face significant more effects on the local climate and smog.

The focus regarding sustainability in the AMA mostly dedicate to climate change, air quality and reduction on the dependency of fossil fuels. Therefore, four relating impact categories are selected from all impact categories. The four impact categories are the KPIs, and are used to conduct a baseline. The selected KPI impact categories are abiotic depletion, acidification, global warming (GWP 100) and photochemical oxidation. The impact assessment on these KPIs resulted in emission quantities of respectively 152.350 (Sb eq.), 7.640 (SO_2 eq.), 7.870.540 (CO_2 eq.) and 860 (C_2H_4 eq.) ton, belonging to the baseline year 2015. By expressing the CO_2 emission quantities in CO_2 per GJ an average of 48.5 kg CO_2/GJ is computed. Comparing the results with relating DHN studies is done to validate the impact assessment outcomes. The emission quantities, obtained by the impact assessment on the baseline KPI impact categories, will be used in the coming chapters to evaluate the environmental profiles of the proposed improvements.

Chapter 5

Technologies and improvements

5.1 Improvements

In this section the technologies that could serve the thermal energy supply are elaborated. Only base load technologies are considered. The base load technologies need to be able to generate a sufficient amount of heat serve the required thermal energy. Therefore, the technologies should be able to generate low-quality thermal energy with temperatures of at least 140°C. Besides, the technologies considered will be centralized technologies such as CHP plants. Decentralized technologies such as data centers and solar islands, which often contain lower temperature heat, are left out of scope.

For each technology a general process review is given. In this process review the current stage of development is evaluated. Also, the technical requirements and parameters that influence the overall efficiency of the DHN are discussed. Therefore, background knowledge on the DHN is studied. Dutch DHNs exist of indirect-connected networks with a supply/ return water temperature of 90/70. To reach this temperatures the water entering the DHN need to be around 140°C, while the return temperature commonly decreases to 40°C. An extended background study of the DHN can be found in Appendix G. Next to these supply and return flow temperatures, common thermal capacities of the technologies are given. These parameters will be used in chapter 6 to propose thermal energy supply configurations. Accordingly, the best suited areas of the technologies are discussed. Both the reuse of current locations and the development on new locations are considered.

Subsequently, an environmental profile for each technology is created. The environmental profiles will be based on a quantitative comparison between each technology and the KPI baseline values of the year 2015, given in Table 4.2. The environmental improvement profiles will be modeled using the Ecoinvent database and Simapro software.

The environmental profile of each proposed processes will be modeled by assuming a hypothetical 100% thermal energy supply of this single technology, e.g. the environmental profile of the geothermal application technology is modeled, assuming a 162,5 PJ direct energy input by geothermal energy. Also the reliability of the proposed technologies are assessed on the three processes criteria; used raw materials, used heat generation techniques and matching capacities, indicated in the methodology subsection 2.2.3.

The LCA processes used for the proposed improvements are selected with caution. When possible, similar technologies from the baseline year, elaborated in **??** are selected. This is done to reduce the unreliabilities between the baseline impacts, and the proposed improvement impacts. In cases of insufficient LCA data from the database, literature reviews will be used as supplementary sources. Depending on LCA data availability, the impact profiles are expressed quantitatively. In cases of lacking data the impact will be expressed qualitatively. The resulting environmental profiles of each technology represent the environmental performance of the technological process, related to the baseline. Processes that perform well compared to the baseline, are favored technologies for the sustainability configurations composed in chapter 6.

5.1.1 Geothermal Applications

General overview

Geothermal energy has the potential to gain a significant share in the energy contribution for the thermal energy supply in district heat grids. Developing deep geothermal energy systems connected to the DHN is frequently mentioned by Minister Kamp (2016, p, 97) of Economic Affairs and will become an important source for district heating. According to Connolly et al. (2014, p. 477) geothermal energy could provide heat at lower cost compared to conventional fossil alternatives, and is therefore included in the "Heat Roadmap Europe" they developed. A diverse range of geothermal applications exist, which are all coherent to the term "geothermal energy". All technologies can be distinguished from each other based on their contrasting operating depths:

- Heat pump, which is a technology that operate at shallow surface layers and operates at depths between 2 to 100m.
- Cold-heat storage, which is a technology that stores heat in the summer and cold in the winter using aquifers at a depths of 30 to 300m.
- Doublet geothermal, extracts thermal energy from deep surface layers which is used for heating and operates at a depths below 1500m
- Enhanced geothermal systems (EGS), generates electrical energy from hydrothermal sources and operates at depths below 5000m

Within the Netherlands cold-heat storage and heat pumps are technologies which are already widely used (Sanner and Nordell, 1998, p. 10). Also in Amsterdam over a 100 different cold-heat storage systems are installed (City of Amsterdam, 2016). These technologies however do not reach the temperatures required to efficiently serve the DHN with thermal energy. These temperatures can only be obtained with doublet geothermal and EGS systems due to its uncompounded task to produce heat.

Therefore, especially the doublet geothermal systems are interesting for implementation into the DHN. Due to the various depths the technology can operate the doublet geothermal systems can optimally be designed to supply heat to the grid. These systems do already exist within the Netherlands and are mostly developed to serve the agriculture industry (Kramers et al., 2012, p. 638).The only geothermal system installed with the purpose to serve heat to the district network is the "Haagse Aardwarmte Leyweg" in the Hague (Lako, Luxembourg, and Ruiter, 1982, p. 23) which has a thermal capacity of 7MW at a temperature of 75°C. Due to its advantages compared to the other geothermal systems the focus of the geothermal section will be on the doublet geothermal technology. Doublet geothermal energy will therefore hereinafter referred to as geothermal energy.

Geographical boundaries

Geographical boundaries for geothermal plants in the AMA should carefully be selected to guarantee the the highest power outputs of the geothermal plant. Suited locations for geothermal energy are the municipalities that lie North of the North Sea Canal. These are municipalities of: Edam-volendam, Landsmeer, Oostzaan, Purmerend, Waterland, Wormerland and Zaanstad.

Currently two geothermal projects are developed within the AMA. First geothermal system is the "Floricultura aardwarmteproject" in Heemskerk with an production temperature of 100°C and a capacity of 10 MW (Platform Geothermie, 2017). The depth of this installation is up to 2.9 km and serves the agriculture sector. Second geothermal installation is located within Haarlem and is currently in construction. The geothermal installation will be in operation in 2019, producing 33 MW during peak demand hours for 6040 households (Andela, 2015, p. 7).

Technical specifications

The heat produced with geothermal energy depends on the depth of the aquifers. According to Ter Voorde et al. (2014, p. 109) the average thermal gradient of deep soils is 33°C/km in the Netherlands. With an average surface temperature of 10°C (KNMI, 2005, p. 11-1) this gives an approximate temperature of 142°C at 4000m depth, high enough to deliver heat directly to the transmission grid. Due to the oil and gas exploration activities within the Netherlands a lot of information on the ground temperatures is acquired. Thereby, over 5000 deep aquifers and 150.000 exploration measurements have been performed in the past (Kramers et al., 2012, p. 638). Models describing the temperature evolution, calibrated with the available measurements are developed by Bonté, J.-D. Van Wees, and Verweij (2012, p. 499). These models revealed that the AMA is perfectly appropriate for geothermal energy extraction (Figure 5.1). Temperatures within the metropolitan area are much higher compared to the Dutch average and gives temperatures up to 154°C. Therefore, aquifers shallower than 4000m could be sufficient to serve the heat desired.

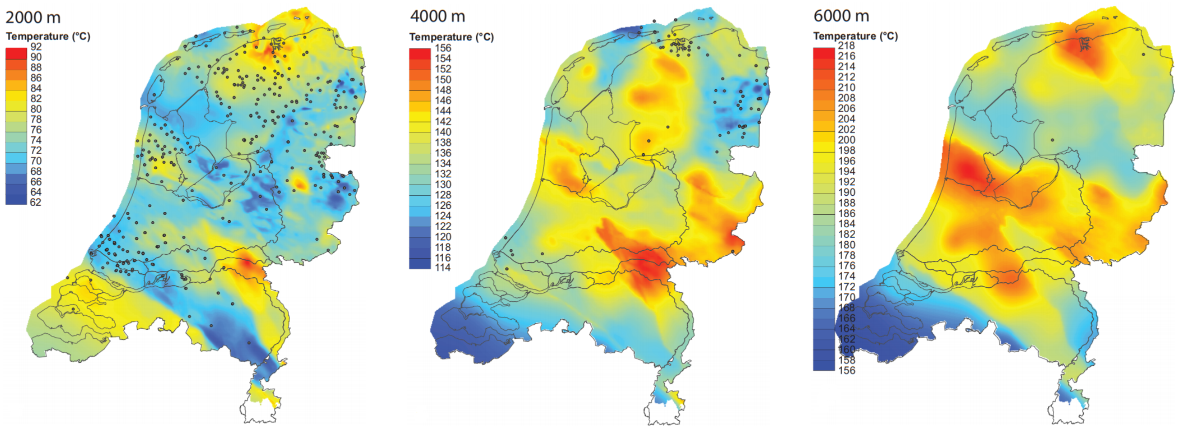

FIGURE 5.1: Increasing temperatures at 2000m, 4000m and 6000m depth (Bonté, J.-D. Van Wees, and Verweij, 2012, p. 499)

Besides the production temperature and aquifers depth, the power output is an important parameter. The power output is a function of the volume flow rate, specific heat and the difference between the production and injection temperature. The power output can be computed with the equation:

$$P_{doublet} = \rho_w C_w Q(T_{production} - T_{injection}) \tag{5.1}$$

Evaluating the equation exposes that the injection temperature, which is the same as the return flow temperature of the DHN, has influence on the geothermal power output. When the injection temperature goes up, the power output goes down. Therefore, low return flow temperatures are preferred when using geothermal energy. Maintaining the power output, e.g. during sudden temperature increase of the return flow water, can also be achieved by increasing the flow rate. Increasing the flows rate means that more water is pumped from the ground. Pumping water from the ground has influence on both the electricity consumption of the pump of the geothermal system, and the lifetime of the geothermal aquifer. The amount of electricity required for the pump can be computed by:

$$P_{pump} = \frac{Q\Delta p}{\eta} \tag{5.2}$$

This equation shows that the electrical pump capacity is depending on the pump efficiency, flow rate and pressure drop in the well. Both equations give valuable insight on the technical requirements of geothermal systems. Therefore, the electricity required by the pump is computed using plausible conditions for the AMA. When assuming a geothermal installation with a capacity of 34 MW_t, a production and injection temperature of 140 and 40°C and heat characteristics of water will give a flow rate [Q] of 295 m^3/h, calculated with Equation 5.1. This is amount of water needed from the ground to deliver a power output of 34 MW_t. Because water is extracted from the geothermal well, the pressure drop increases over time. This means that the pump selected should be strong enough to deliver the power required at the end of the lifetime of the well. The average pressure drop ranges from 2.5 MPa, at the beginning of the geothermal energy production, to 5 MPa at the end of its lifetime (Doddema, 2012, p. 46). Assuming a pump efficiency of 75%, a flow rate of 295 m^3/h and a pressure drop of 5 MPa provide an electrical pump requirement of 2 MJ_e, computed with Equation 5.2. Hence, the electrical requirements are considered to be low, compared to the thermal output.

The sustainability of geothermal energy is often called into question. Reason of this debate is because at a certain point the geothermal well is exhausted, and can not supply the heat requested. However, the lifetime of the well, and its recovery time needed are such long that most scientist consider this technology to be sustainable (Rybach, 2003, p. 469). The lifetime of a well depends on many factors of which the well spacing, the flow rate, and the temperature differences between the initial well temperature and the production temperature has major influences (Crooijmans et al., 2016, p. 209). These parameters provide the breakthrough time of the well. The breakthrough time describes the time it takes to reach the end of its lifetime, and is defined by a well temperature of 90% of the initial temperature (C. F. Williams, 2010, p. 4). According to Doddema (2012, p. 25) a breakthrough time of 40 years can be achieved considering a flow rate of 295 m^3/h, and a well space size of 2000 meters. This size can easily be realized for a geothermal system with an operation depth of 3km (Doddema, 2012, p. 25). The replenishment time is the time the geothermal well needs to recover to its initial state. This is often defined as 95% recovery, starting at the breakthrough time. The replenishment time is generally reached within the same time scale as the lifetime of the well (Rybach, 2007, p. 465).

Next to the limited lifetime of a geothermal well, the methane production also raises sustainability questions. The production of methane is a common by product when pumping the hot water from the well. During the exploitation of hot water for geothermal energy, significant amounts of methane is pumped up. According to Blok (2017), this amount can be as high as 50% of the total volume that is pumped. This excess gas is subsequently combusted, causing extra emissions. Because the amount of water that need to be pumped is known, it is possible to compute the methane quantities that comes along with the water. As aforementioned a geothermal plant with a capacity of 34 MW_t requires a water flow rate of 295 m^3/h. When 50% of the volume is methane this will mean that also 295 m^3 of gas comes up per hour. This is equal to 2.58 million m^3 methane per year. Considering a complete combustion of methane (CH_4) gives the emissions CO_2 and H_2O. Based on the molar masses of the chemical compounds it can be derived that, considering a complete combustion, 2.6 million m^3 methane will lead to 753.3 ton CO_2 emissions per year for a geothermal plant with a capacity of 34 MW_t. The emissions that occur by the methane capture and storage processes are not considered in the secondary CO_2 emission calculations. The emissions coming from the methane capture and storage techniques are left out of scope.

Environmental performance

The environmental improvements are modeled using the Simapro software. The impact of the geothermal improvement is modeled as 100% thermal energy delivered by geothermal energy. This is done to make this technology comparable with baseline of the year 2015. The process selected from the Ecoinvent database is identical to the process described in Table 4.1. Because the best matching alternative process in Simapro produces electricity, allocation on the steam price is used to determine the impact. Additional, the CO_2 emissions emitted by the methane combustion are added to the LCA results. This is done to expose the proportions of the methane combustion emissions, relating to the heat production of the geothermal installations. If the entire direct energy input comes from geothermal installations with a capacity of 34 MW_t, a sum of approximately 150 different geothermal plants will be needed. Combined they will annually produce 391.5 million m^3 methane. This is equal to approximately 114.100 ton CO_2 by the combustion of methane.

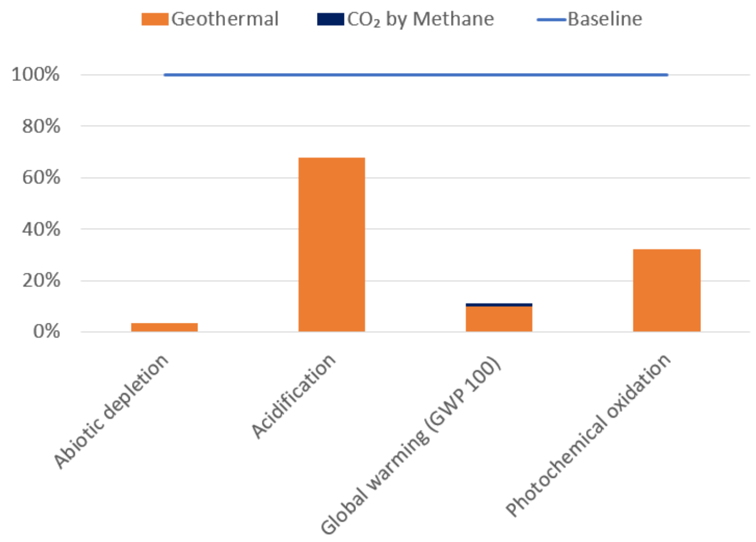

FIGURE 5.2: Environmental performance of geothermal energy on the selected KPIs related to the baseline impact in the year 2015

Figure 5.2 reveals that geothermal energy generation can provide significant environmental improvements on the KPI impacted categories. Mainly the reduction of abiotic depletion and global warming potential realize significant reductions. The CO_2 emissions emitted by the combustion of methane only have a minimal effect on the total CO_2 emissions. The KPI with the lowest environmental improvement is the acidification category. This comes due to the negative effect of the acidic fluid injections used. This fluids is used stimulate the aquifers to pump up the hot water. The acidic fluids creates precipitation and dissolution of the minerals in the aquifers, and therefore contribute to the low scores on the acidification category (Taron and Elsworth, 2009, p. 858). When taking the remaining impact categories into account only fresh water aquatic eco-toxicity and terrestrial eco-toxicity comply no improvement relating to the baseline.

TABLE 5.1: Additional delineation of the selected geothermal LCA process from the Ecoinvent database

Selected process	State of art	Process description
Electricity, high voltage electricity production, geothermal	2008	Geothermal plant process used to model the LCA dataset in the Ecoinvent 3 database is based on the study of Bertani (2012). For the modeling of geothermal energy a general form of geothermal electricity generation is used. No exact technology match could be found, the best fitting solution therefore describes the generation of high voltage electricity. The selected process is modeled based on a binary cycle plant which has an average capacity of 5MW. The process includes: "all operation and maintenance activities and materials of the power plants. The loss of the working medium is included. This dataset includes cooling water, but no cooling infrastructure"

Reliability

Used raw materials	- Not applicable
Used heat generation techniques	- Inadequate
Matching capacities	- Sufficient

Based on the processes described in the LCA process, and the purpose of thermal energy supply by geothermal sources is can obtained that the reliability is inadequate. Uncertainty lies in the extra proceedings made in the LCA to generate electrical energy.

Assumptions

- Emissions of electrical generation geothermal installations is equal to heat producing geothermal applications
- Similar electricity requirements of the LCA process

5.1.2 Biomass power plant

General overview

The biomass technique elaborated within this section is the energy generation by direct combustion of pellets, wood-chips and pruning wood wastes. Although the combustion of biomass is the oldest from of energy generation known, it is a very complex compound to manage due to the distinct phases it encompass. The interactions between thermal and mass fluxes have only recently been understood (Jenkins et al., 1998, p. 18). Important misunderstanding is that the solid biomass itself does not burn. During the combustion of biomass the solid compound consumes heat to maintain a drying and volatilization processes which on their turn chemically convert the solid biomass into fuel gases, volatile liquids and char residues. The fuel gases and volatile liquids released generate heat after combustion. When the gases and volatile liquids are burned a char combustion can be activated which require oxygen, carbon dioxide and water vapor to create the fuels oxidized carbon and hydrogen and ash. This biomass combustion process is called the pyrolysis process and is depending on the temperature and the heat flux which environ the solid biomass (Koppejan and Van Loo, 2012, p. 9).

The production of heat from biomass in the AMA, is currently produced at CHP plants located in Purmerend and Lelystad. These biomass power installations bear considerable environmental improvement potentials in the metropolitan area. Beside the emissions originating from direct biomass combustion it is considered to be carbon-neutral due to the closed carbon cycle loop. The emitted carbon emissions are absorbed by photosynthesis of new growing vegetation and is therefore a good alternative to fossil fuels (Heinimö and Junginger, 2009, p. 2949). Based on this carbon cycle the combustion of forest waste biomass does not contribute to an increasing carbon balance in the atmosphere and is a good alternative to combat climate change (Stupak et al., 2007, p. 2). It is however essential to use biomass originating from forest waste such as pruning residues. When using energy corps from agriculture to produce biomass stock loss of biodiversity and competition between food crops is created (A. Evans, Strezov, and T. J. Evans, 2010, p. 1421).

The supply of the biomass required could however create emissions and logistical complications. Especially when located within urban areas the supply of biomass could cause additional emissions due transport (Vliet et al., 2016). Therefore the location of the of a biomass CHP system has large influence on the sustainability of the installation (Beer, Slingerland, and Meindertsma, 2014).

Geographical boundaries

To decrease the emissions occurring due transport and to maintain efficient supply logistics it is important to locate a biomass plant close to the biomass sources, which is often close to a forest. Although the emissions of the biomass plant is regard to be carbon neutral it still emit emissions. These emissions can yield negative effects on the air quality of urban areas. Therefore urban centers should be avoided. The length of the transmission grid should however be minimized in order to limit the heat loss through the supply pipes. All together determining the locations of a biomass plants contains lots of variables which have to be considered. When focusing on climate change however a location close to the sources is undoubtedly prioritized.

Technical specifications

The technical design features of biomass plant combustors differ a lot compared to the design of, for example, coal plants. This difference is occurred due to the high amount of volatile compounds which can be released during the pyrolysis stage of the biomass fuels. There are many types of fuels which all belongs to the biomass category such as oils, organic fats and solid woods. All containing a high volatile content, often exceeding the 80% (Overend, 2009, p. 4). The majority of CHP plants use however wooden biomass.

The highest combustion efficiencies are reached in biomass plants with separated combustion and heat transfer cambers. Biomass plans with open fires lose significant amounts of heat through radiation into space and convection with the excess air. The air excess have, together with the moisture content of the biomass a substantial influence on the efficiencies of the CHP plant. Based on separated combustion chambers, the combustion efficiencies can be express by (Overend, 2009, p. 5):

$$\eta = 96.84 - 0.28MC - 0.064\Delta T - 0.065EA \tag{5.3}$$

In this equation MC is the percentage of moisture in the biomass,typically ranging around 50% (Overend, 2009, p. 5). The ΔT is the temperature difference between the cooled flue gas within the chimney and the outside room temperature. EA is the excess air, and describes the minimum amount of air required for full combustion of the biomass. This value is given in a percentage, usually ranging between 25 to 100% (Overend, 2009, p. 5). As can be obtained from Equation 5.3, a smaller ΔT increases the biomass power plant efficiency. In a DHN system, the return water is used as coolant of this flue gas. Therefore, it is important to maintain low return water temperatures to increase the power plant efficiency.

Environmental performance

The LCA process selected for this technology is identical to the process used to create the environmental profile of the baseline, created in chapter 4. This process contain a relatively small share in the baseline year 2015, with only two relatively new biomass power plans located in Purmerend and Lelystad. The proposed improvement is similar to the current biomass plants in Purmerend and Lelystad. Therefore, the same alternative LCA process, described in section 4.2, is used to model the environmental profile of biomass. Figure 5.3 shows the results of the biomass improvement, modeled with the Simapro software. Assumptions made on this process is that the biomass combustion is based on a wood chip supply. From the LCA results it can be concluded that the use of biomass as main energy source lead to improvements on abiotic depletion and global warming potential. However, the photochemical oxidation impact category will, when considering a thermal energy supply of only biomass combustion, increase significantly. The increase photochemical oxidation emissions can lead to smog and air pollution. This is a large disadvantage of using biomass as energy source, and is also observed by Booth (2016, p. 1-2). The pollutions related to the logistics and transport of the biomass is not taken in to account in this LCA process. Also, the land use competition could face disadvantageous impacts when biomass combustion will more frequently be used.

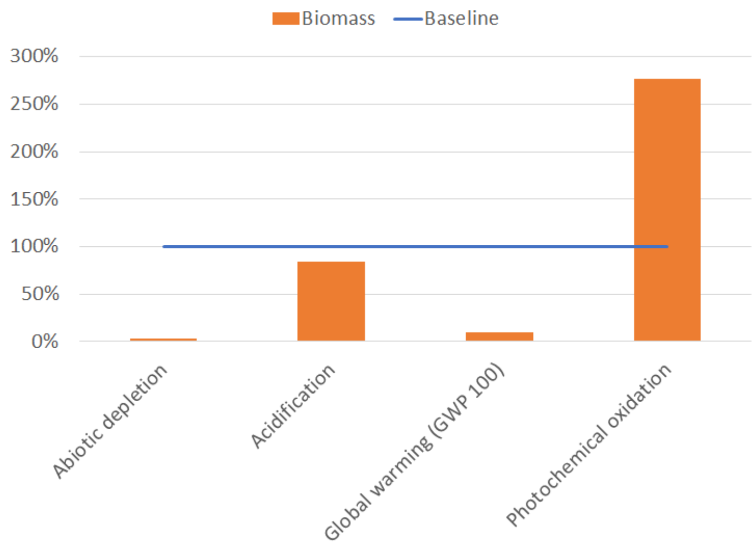

FIGURE 5.3: Environmental performance of biomass on the selected KPIs related to the baseline impact in the year 2015

TABLE 5.2: Additional delineation of the selected biomass LCA process from the Ecoinvent database

Selected process	State of art	Process description
Heat production, mixed logs, at furnance 30kW, state-of the-art 2014 RoW	2014	Most relating process which describes the combustion of pruning forest waste of the biomass plants located in Purmerend and Lelystad is the process which describes the combustion of wood logs in a Swiss furnace installed in 2014. This process is globally used as first approximation. The ecoinvent process includes: "the combustion of natural wood logs in a modern boiler. Included are the infrastructure, the wood requirements, the emissions to air, the electricity needed for operation, and the disposal of the ashes." The capacity range is 10-50 MW which covers both biomass plants in the AMA

Reliability

Used raw materials	- Sufficient
Used heat generation techniques	- very corresponding
Matching capacities	- Very corresponding

The reliability of the biomass process is considered to be reliable. The state of art of this technology is accurate and processes are very related.

Assumptions

- Biomass combustion is based on a wood chip supply.
- Geographical boundaries of this swiss biomass furnace are similar the proposed biomass combustion standards

5.1.3 Biogas power plant

General overview

The sources used for the combustion of biomass are very similar to the sources required for the production of biogas. Biogas is a mixture of various gaseous compounds which is produced from oxidized organic substances. When used in a CHP, the gas can either be supplied by third parties or produced within the plant by gasification.

The only biogas currently used for the thermal energy supply in the DHN is processed by AEB Amsterdam. AEB obtains its biogas from sewage treatment plants (Dutch: RWZI) which process waste sludge by anaerobic fermentation to produce the gas (d. J. Swart, Pranger, and Kappelle, 2016, p. 31). The current biogas yield of all RWZIs in the Netherlands is 84 million m^3 per year, however, when the fermentation process of the existing sewage techniques is improved a potential production improvement of 75% can be obtained (Coenen, Gastel, and Jong, 2005, p. 4). In total the AMA contains thirteen RWZIs on different locations, which therefore have the potential to be used as biogas suppliers for an expanded DHN (Voskuilen and Bremer, 2016, p. 11). The production of this biogas from current sewage installations requires additional energy. This makes the thermal energy production from biogas less efficient than it suggests. When shifting to new decentralized sewage systems, e.g. by using vacuum toilets combined with organic kitchen waste, the energy requirements for the biogas production can be reduced wile acquiring higher biogas production rates (Zeeman, Sanders, et al., 1997; Zeeman, Kujawa, et al., 2008, p. 1208).

Different biogas process is the production of biogas by biomass gasification. This process is sometimes used in biomass power plants. Although the resources biomass are similar, the gasification technique provides higher efficiencies relative to direct combustion (Gielen, 2012, p. 5). Direct biomass combustion is often only used for thermal applications, and gasification is generally used for combined power generation. The production of electricity and heat by biomass gasification contains a generation ratio that produces approximately two times more thermal energy relative to electrical energy. Therefore, heat production through gasification is suitable for district heat supply McKendry, 2002, p. 62; Kirubakaran et al., 2009, p. 181.

Advantage of biogas combustion by both biogas obtained from production of sewage treatment plants, and biomass gasification is that this processes can replace natural gas in existing plants. Due to similar heat contents, the gas turbine energy output will be identical when using biogas. Accordingly, this means that the existing gas infrastructure can be maintained. When natural gas CHP plants are adjusted with a centralized gasification system, only a gasification boiler needs to be applied before it can be put into service (Ahrenfeldt et al., 2013, p. 1413).

Geographical boundaries

The geographical boundaries of biogas power plant are restricted to the locations of the current power plants. This way existing technologies and infrastructures can be used to supply sustainable thermal energy to the DHN. All gas based plants are listed in Table 5.3. The blast furnace gas power plants can be recognized by *. These power plant types are fueled with the gaseous by-products from the iron ore processing industry.

TABLE 5.3: Gas turbine powered power plants within the AMA (Seebregts and Volkers, 2005)

Name	Technology	Capacity [MW_e]
Almere-1	STEG	67
Almere-2	STEG	53
Diemen-33	STEG	249
Hemweg-7	Combi	599
IJmuiden 1*	STEG	145
Purmerend-1	STEG	69
Velsen-24*	Conventional	459
Velsen-25*	Conventional	360
Velsen-GT1	Gas turbine	26

The only power plant which is currently connected to the DHN is the Diemen 33 plant. If the high fuel requirements of this natural gas plant can be reached by biogas, it is possible to replace the current fossil fuel by a sustainable alternative. Following the capacities of this plant can be maintained.

Technical specifications

The working principal of thermo-chemical biomass gasification to biogas, is based on thermal treatment of organic material in a oxygen-free environment. This thermal treatment produces a biogas consisting of CO, CO_2, H_2, CH_4 and N_2 (Bridgwater, 1995, p. 639). This process can be performed with several gasification techniques. The most common ones are the fixed bed gasifiers and fluidized bed gasifiers. Only the fluidized bed gasifiers can reach thermal capacities sufficient for a DHN (Gielen, 2012, p. 14).

The biogas produced by the gasification process, or obtained by the biogas production from the sewage treatment plants, is combusted in a gas turbine. The parameters that determine the the efficiency of biogas combustion depend on the gas turbine design. To understand the effect the DHN has on the thermal energy output of biogas combustion, some of the technical aspects of a gas turbine are explained.

Gas turbines are advanced power generators that work a different than conventional steam power plants. In a steam power plant the working fluid, often water, changes from a liquid to a gaseous phase after which it returns to it original phase. In a gas turbine no phase changes occur because the working fluid remains gaseous. In this process only the chemical composition of the gas changes through combustion (R. E. Sonntag et al., 2003, p. 477). Accordingly, the energy generated is determined by the difference between the work required to compress the gas with a compressor, and the work performed in the turbine by decompression through combustion of the gas (Consonni, 1995, p. 9). The working principles of a gas turbine has influence on the performance and the associated efficiencies. The efficiency of a gas turbine can therefore be determined with the Brayton cycle (R. E. Sonntag et al., 2003, p. 477):

$$\eta_{th} = 1 - \frac{Q_{cold}}{Q_{hot}} = 1 - \frac{\dot{m}C_p(T_4 - T_1)}{\dot{m}C_p(T_3 - T_2)} \tag{5.4}$$

In this expression the Q_{cold} is strongly influenced by the inter-cooling system, cooled with return water of the the DHN. The inter-cooling system decreases the work required to compress the gas which makes the turbine more efficient (Reale, 2004). Therefore, when using gas turbines to incinerate biogas as heat source for the thermal energy supply of the DHN, it is important to keep the return water of the grid as low as possible.

Environmental performance

Using biogas as heat supply technology, environmental improvements can be made regarding the environmental impact categories. The LCA process selected, to compose an environmental profile for biogas, is the exact same as the process used for the environmental performance of the baseline year. The LCA process obtained from the Ecoinvent database is composed by Jungbluth et al. (2007, p. 184-196). The process includes the combustion of biogas in an co-generation unit with a biogas engine. Unfortunately, no biogas production by either sewage sludge waste, or gasification with matching capacities could be obtained. Therefore, the process selected produces biogas from agriculture. The impact assessment of the biogas heat generation is showed in Figure 5.4. The results of the impact assessment exposes significant environmental improvements of all KPI categories, relating to the baseline. Especially, the abiotic depletion and global warming impact categories result in major environmental improvements. However, using biogas combustion could lead to an increase of acidification and eutrophication. According to Whiting and Azapagic (2014, p. 185) the impacts relating to acidification and eutrophication can increase significantly relating natural gas.

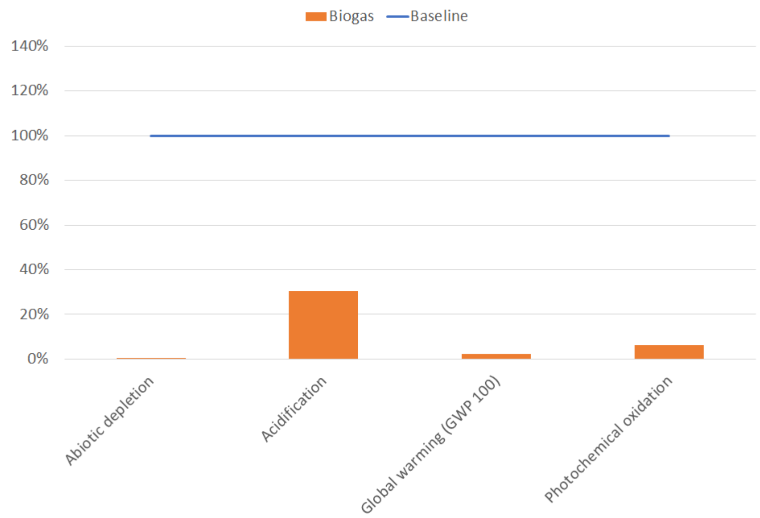

FIGURE 5.4: Environmental performance of biogas on the selected KPIs related to the baseline impact in the year 2015

TABLE 5.4: Additional delineation of the selected biogas LCA process from the Ecoinvent database

Selected process	State of art	Process description
Heat, at cogen with biogas engine, agricultural covered	2007	Process describing the biogas combustion is conducted by Jungbluth et al. (2007, p. 184-196) by use of biogas in a co-generation unit. Included processes are: "emissions to air, biogas consumption, use and disposal of operational supplements as well as infrastructure expenditures." The output of this process is, agriculture covered with biogas engine and delivers the co-products: "heat and electricity, at cogen with biogas engine, agricultural covered". The degrees of efficiency are as follows: electricity: 33% and heat: 67%. ; Geography: Conditions of co-generation in Switzerland.

Reliability

Used raw materials	- Sufficient
Used heat generation techniques	- very corresponding
Matching capacities	- Sufficient

The generation techniques used are similar to the proposed biogas improvements, which makes the selected process reliable. However, the production of biogas from agriculture leads to uncertainties. Also the state of the technology can be outdated.

Assumptions

- Biogas emissions on the KPI categories of biogas produced from the agriculture industry is similar to the emission of biogas obtained from sewage plants.
- Similar efficiencies of the biogas engines are used.

5.1.4 Hydrogen power plant

General overview

Similar to natural gas, hydrogen is suited to be used as fuel within combustion turbines. Accordingly, hydrogen can supply heat to the DHN through hydrogen CHPs. The possibilities of hydrogen injection and full replacement of natural gas power plants by hydrogen of larger sized gas turbines have been investigated and reveal promising results (Juste, 2006, p. 2112; Chiesa, Lozza, and Mazzocchi, 2005, p. 73). Hydrogen combustion turbines are auspicious alternatives which potentially emit no farm-full emissions after ignition, and can lead to low cost energy generation (P. A. Pilavachi et al., 2009, p. 9). Hydrogen production and energy generation could, mainly in countries with an expanded gas distribution network, be a valuable technology (Dodds et al., 2015, p. 2065). Due to the extensive gas network and offshore wind energy production the Netherlands, and predominantly in the Northern areas, are perfectly suited to implement this technology in the Dutch energy infrastructure (Wijk et al., 2017, p. 47). However, before this technology can be implemented the production phase have to be optimized. Currently the production of hydrogen requires a significant amount of energy which makes the technology relative expensive. Therefore, hydrogen is more often used as energy carrier than a power generation fuel (P. A. Pilavachi et al., 2009, p. 4).

The production method of hydrogen specifies whether this technology is sustainable. There exists a range of technologies which can be subdivided in three different production categories(IEA, 2006, p. 5; Ibrahim Dincer and Zamfirescu, 2016, p. 77):

- Gasification conversion
- Electrolysis
- Biological process

Gasification conversion technology considers thermal hydrogen production from hydrogen-rich carbonaceous substances and is seen as an effective production method (Stiegel and Ramezan, 2006, p. 187). This method creates chemical reactions within the carbonaceous substances using steam in order to release the hydrogen parts. The technology is mostly dedicated to fossil fuels but can however also be performed on biomass (Christopher and Dimitrios, 2012, p. 6640). The production of hydrogen from natural gas using thermal energy is currently the most frequently used method (Demirbas, 2009, p. 111)

Electrolysis produces hydrogen with electrical energy that dissolves water with catalysts. There are two common techniques, both established with the electrolysis method. These are the alkaline electrolysis, this technology is already commercially executed, and the polymer electrolyte membrane (PEM) water electrolysis. The PEM technology has the potential to become a competitive production method (Ibrahim Dincer and Zamfirescu, 2016, p. 101; Diéguez et al., 2008, p. 7339).

Biological processes describes the production of hydrogen by formation from natural mechanisms. This mechanism rarely occur within nature however, some bacteria and algae species can decompose water from organic matter (Demirbas, 2009, p. 166). These biotechnological processes are very valuable sustainable processes and could offer remarkable advantages. Some bio-processing methods, and recent developments have been reviewed by Kapdan and Kargi (2006, p. 571-575). The most promising technologies are among others; bio-photolysis by algae, microbial and anaerobic fermentation of biomass and dark and photo-fermentation of organic materials.

Most promising improvement relating to the thermal energy supply within the AMA is the reinstatement of existing natural gas power plants with hydrogen fuel. In order to guarantee a sustainable supply, and reduction on the impact categories, hydrogen produced with electrolysis is currently most viable. Therefore, only hydrogen produced by electrolysis is considered in the impact assessment. However, the biotechnological alternatives are technologies with high potentials, and could become an essential production method in the near future. These technologies have the advantage to consume energy amounts and require limited material accessories.

Geographical boundaries

Similar to the biogas improvement the thermal energy production by hydrogen in adjusted gas turbines is geographically bounded to the existing locations of the present gas turbine plants. The gas turbine power plants within the AMA, which are as well suited to hydrogen energy generation, are all listed in Table 5.3.

After modification of one or more of these listed power plants it can supply heat directly into the transmission grid. All locations have the advantage that they can rely on the existing gas infrastructure. However, the infrastructure will require significant adjustments to become suitable to distribute hydrogen. The excising infrastructure is not capable of distributing hydrogen, and will raise the risks of leakages. Due to the smaller molecules of hydrogen, this risk is considerably larger than using natural gas (Haeseldonckx and D'haeseleer, 2007, p. 1383). When the cost efficiency of a hydrogen CHP is increased it can serve as a sustainable base load power plant. With the current production costs however, it is more likely to serve heat during peak demand hours. As mentioned, the efficiency of a modified gas power plant will practically the same as before the modification. Therefore, as long hydrogen requires more energy than it could generate it will remain a backup energy carrier.

Technical specifications

Experiments focusing on the adjustment of modern turbine installations, designed to run on natural gas, turned out that the best strategy to properly operate a gas turbine on hydrogen, can already be reached by adjusting the geometry of the vanes of the turbines stator (Chiesa, Lozza, and Mazzocchi, 2005, p. 75). This adjustment influence the running speed of the turbine, that need to be adapted due to contrasting fuel characteristics. The adjustments of the turbine will lead to a minimal efficiency decrease, wile the total power output can be increased (Chiesa, Lozza, and Mazzocchi, 2005, p. 76).

According to Dodds et al. (2015, p. 2079) using hydrogen and fuel cell technologies for heating is a reliable, and commercially a viable energy generation technique. Also, this technology can rely on satisfying safety records. To accomplish sustainable improvements, the energy generation by hydrogen is depending on the type of electrical energy used for the electrolysis production method. How this electrical energy is produced largely determines how "clean" the energy generation from hydrogen is. Therefore, the electricity used for the hydrogen production should be obtained from sustainable energy sources, such as wind and solar energy.

As aforementioned there are two electrolysis production techniques, alkaline electrolysis and PEM. Both production techniques have different hydrogen production rates. Alkaline electrolysis reaches the highest production rate. The production capacity is expressed in kg H_2 per hour. Commercial alkaline electrolysis have a production yield, ranging between 40 to 2.500 kg H_2 per hour. The electrical energy requirements to reach this production speed is equal to 180 MJ per kg H_2 (Bertuccioli et al., 2014, p. 10). The PEM water electrolysis technique can produce 0.01 to 2.5 kg H_2 per hour, with a potential production of 20 kg H_2 per hour. Also this technique requires an energy input of 180 MJ per kg H_2. The quality of hydrogen from the PEM technique is better than the hydrogen produced with alkaline electrolysis (Bertuccioli et al., 2014, p. 11). Consider the amount of electrical energy required for both production methods, it can be concluded that it requires more energy to produce hydrogen, that it potentially can produce.

Environmental performance

No studies on the combustion of hydrogen are available. Therefore, only the required amount of hydrogen to heat the AMA is computed. The energy content used is given in Appendix A. Also, a turbine efficiency of 50% is used. The impacts occurring due to combustion are not included in this impact assessment. Due to the absence of carbon in hydrogen fuel, the emissions created by the combustion of hydrogen do not contain any from of hydrocarbons. The only emissions from hydrogen combustion are nitric oxides, originating from air due the high temperates that prevail (De Boer, McLean, and Homan, 1976, p. 164).

Unfortunately, the results of the simulations achieved with Simapro diverge too much from results obtained from literature. Therefore, the impact assessment on the production of hydrogen is based on electrolysis, using data from literature. Data on the production is obtained from research results performed by Suleman, I Dincer, and Agelin-Chaab (2015, p. 6983-6985).This impact assessment considers two forms of electricity supply, from wind and solar. The impact results are given in Figure 5.5. From results on the KPI impact categories it can be concluded that producing enough hydrogen to reach the required direct energy input of the AMA lead to environmental improvements in all impact categories. The acidification category based on production with electricity from solar cell, preforms worst. However, this category is still an improvement compared to the baseline. Unfortunately, nu distribution of hydrogen is included in the LCA analysis. This will results additional emissions. Assuming that limited emissions are released by the combustion and distribution phase, it can be concluded that producing heat by hydrogen can result in environmental improvements.

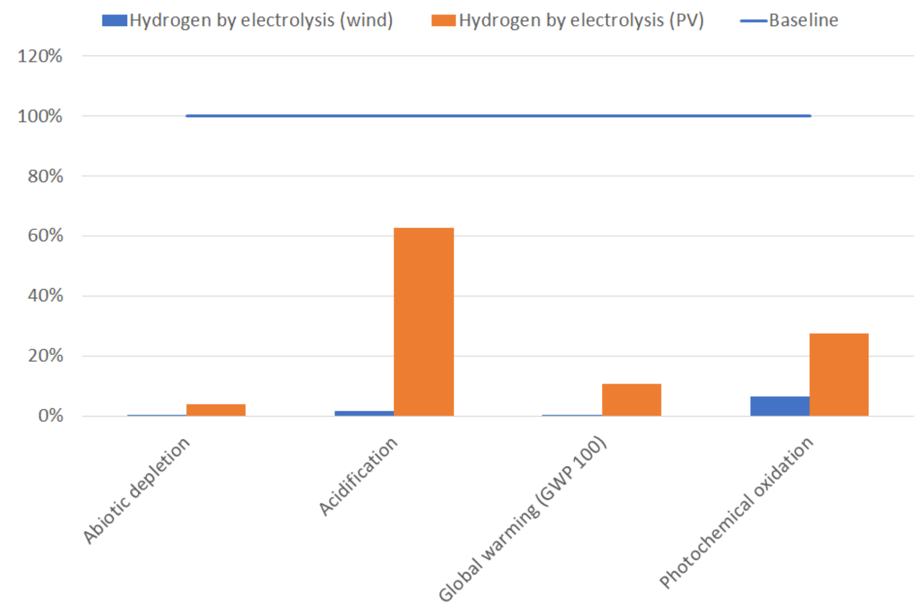

FIGURE 5.5: Environmental performance of hydrogen on the selected KPIs related to the baseline impact in the year 2015

TABLE 5.5: Additional delineation of the selected hydrogen LCA process from the Ecoinvent database

Selected process	**State of art**	**Process description**
Hydrogen production through wind energy	2015	This lca study is performed by Suleman, I Dincer, and Agelin-Chaab (2015) and analyses the production process of hydrogen with electrolysis by using wind and solar power electricity. The data describes a Na-Cl electrolyser. Electricity used are obtained by wind and a solar power plant. The wind in produced by a wind power plant with a capacity of 800 kW. Electricity produced with solar power comes from a 1 kWh solar power plant. The electricity from the wind and solar power plant send to a hydrogen production system. Here an electrolyser converts the electricity to hydrogen.

Reliability

Used raw materials	- Sufficient
Used heat generation techniques	- not applicable
Matching capacities	- not applicable

This process is considered to be unreliable considering the production of heat from hydrogen. However, because the production process of hydrogen mostly determines its sustainability this LCA method could give valuable information.

Assumptions

- The combustion of hydrogen will lead to a minimum amount of emissions
- No distribution of hydrogen is included.
- Hydrogen power generation efficiency of 50% to determine the required quantity of hydrogen

5.1.5 Floating Phase Changing Materials

General overview

Phase changing materials (PCM) is the comprising term of substances that can store energy during phase transition. This is possible with materials that have high heat of fusion characteristics. Such materials are salt hydrates, paraffin, sugar alcohol and salts (Klop, 2013, p. 5). The working principle of PCMs is based on the amount of energy that can be absorbed or released during a heat exchanging processes. This energy is called latent heat. In these materials large amounts of energy is stored during the change between two phases. When solid materials transform to liquid substances, melting of a material, heat is stored. When the substances congeal, the opposite happens and heat is released. The charging principle of PCM is accomplished by adding heat e.g. originating from industrial processes. This heat flows along the substances through a heat exchanger. The heat causes the PCM to melt until it reaches the temperature required. During this stage the materials remain solid. When this stored heat is needed, an opposed reaction is activated. This activation is caused by cold return water, from the DHN (Zondag et al., 2017, p. 4).

This technology can perfectly be applied in the processing industry. In this sector, a large variety of companies have processes with temperatures around 100 to 250°C. Currently this heat is discharged into the environment (Vaartjes, 2017, p. 34). The Energy Research Centre of the Netherlands (ECN), started a project to realize the storage of industrial waste heat with PCMs. This project is called "LOCOSTO" and is financially supported by the Netherlands Enterprise Agency (RVO) (Boer, 2017, p. 3). Design of the PCM storage tank is based on an industrial standardized shell and tube heat exchanger, surrounded by a working fluid. Working fluid used to store heat is magnesium-chloride. This material melts at a temperature of approximately 120°C (Vaartjes, 2017, p. 35; Zondag et al., 2017, p. 10). Installing PCMs on a floating vessel gives the flexibility to charge heat at industrial units, often located near waterways. Subsequently, the heat is released in the DHN. This way multiple processing industries can deliver heat via charging stations, without physically being connected to the DHN. This technology is still in development. Nevertheless several companies like Deen Shipping, INB and the Port of Amsterdam showed interest in this technology (Klop, 2013, p. 10).

Geographical boundaries

The operation location of floating PCMs is not geographical bounded to a single location. It operates in the infrastructure of the inland waterway systems, frequently presented within the Netherlands. Suited waterway is the North Sea Canal (Dutch: Noordzeekanaal). This is a trunk route and key waterway from the coastal city IJmuiden to Amsterdam (Brolsma and Roelse, 2011, p. 28). From Amsterdam it is possible to reach Lelystad, the one of the most Northern bigger cities of the AMA. Multiple discharging locations positioned along this route, could result in DHN construction savings while a high flexibility is reached.

Technical specifications

The energy storing capacities of PCMs range from -35 to 120°C. These materials contain an enthalpy of fusion ranging between 50 to 300 kJ/kg (Zondag, 2010, p. 9). The phase changing material Magnesium-chloride has been tested over multiple cycles to reveal its thermodynamic behavior. The tests showed a charging melt temperature of 117°C, and a discharge congeal temperature of 97°C. The associated enthalpy of fusion value is 169 kJ/kg (Boer et al., 2017, p. 10). This initiate a heat distribution efficiency of 82.9%. The associated flow rate of the tested magnesium-chloride units is 220 m^3/h, with a maximum supply capacity 3.4 MJ/s. The average energy output for a longer time scale is 1.6 MJ/s (Boer et al., 2017, p. 19). Ideally, the magnesium-chloride units will be installed on a floating vessel that can store 28 parallel connected units(Boer et al., 2017, p. 13). Combined, the 28 units will have a total capacity of tot 23 GJ. Based on the test results, this vessel could be charged in 16 hours, and discharged in 4 hours (Boer et al., 2017, p. 19).

The discharge temperature of 97°C means that PCM can not foresee the required temperatures of the DHN. However, the characteristics of high density polyethylene (HDPE), are presumably better suited to deliver heat to the DHN. This substance can deliver higher temperatures and has a discharge temperature of 120°C. Therefore, it can deliver the higher temperatures currently required (Boer et al., 2017, p. 11).

Environmental performance

The emissions of this technology occur from the production of the PCM, and the transport of the floating vessels. Because the production emissions are only released once, it is difficult to compare phase changing materials to the environmental performance of the baseline year. Therefore, the sustainability of PCM is evaluated without using LCA simulations.

It is assumed that most emissions occur by the transport of the PCMs. Therefore, focus on potential environmental improvements by PCMs lies on the transport. Route selected to estimate the emissions is the inland waterway between IJmuiden and Amsterdam. The distance between the two cities is approximately 30km. According to Boer et al. (2017, p. 20) it is assumed that one floating vessel weight approximately 2800 ton, and can make approximately 300 charge-discharge cycles per year. This means that one vessel travels 18.000 km per. The average emissions per kilometer for an inland ship in the Netherlands, weighting between 2000 to 3000 ton, is 40.1 kg CO_2 and 0.04 kg SO_2 per km (Denier van der Gon and Hulskotte, 2010, p. 42). For the selected route the total emissions will reach 722 ton CO_2 and 0.8 ton SO_2, annually per ship. If, hypothetically, PCM will serve the full direct energy input requirements of the AMA, it means that, based on a capacity of 23 GJ per vessel, an incredible amount of nearly 12.000 vessels will be required. This results in approximately 8.5 million ton CO_2 and 9100 ton SO_2. Comparing the emissions with the baseline emissions of CO_2 and and SO_2, given in Table 4.2, means an increase of emissions in both categories. Therefore, it could be concluded that the heat supply by PCM will not give significant environmental improvements when using the available transport technologies.

5.2 Improvements conclusion

Goal of this chapter is to give insight in the environmental performance of different technologies, that potentially can be implemented to the DHN. With this information the second sub-question, given in section 1.4, is answered. Sub-question two is stated as follows:

What are the options to reduce the environmental impact of the thermal energy production and supply in the Amsterdam metropolitan area?

To answer the second research sub-question five different technologies are extendedly elaborated. The technologies are assessed on; their potential to be implemented in the DHN, technical characteristics, and environmental performance. The technologies selected are; geothermal energy, biomass, biogas, hydrogen and phase changing materials. Each technology can lead to improvements on the environmental impact of the thermal energy production. The main findings comprise that environmental improvements can be made to make environmental reductions on the selected KPI impact categories. Geothermal energy is a technology that is suited to be implemented in the AMA. This is mainly due to high ground temperates located North of the North sea Canal area. This makes the development of geothermal energy interesting for mainly the municipalities of: Edam-volendam, Landsmeer, Oostzaan, Purmerend, Waterland, Wormerland and Zaanstad. Also the thermal energy produced with biomass lead environmental improvements. However, the distance to the plant, and origin of the biomass is highly important. Using biogas yield in considerable environmental improvement. Currently is source is obtained from sewage treatment plants. Increase of biogas from sewage plants is possible. This would however be a little increase. Therefore, production of biogas can probably be challenging. Hydrogen can potentially provide substantial environmental improvements. However, with current production techniques it cost more energy to produce hydrogen than it could potentially produce. Therefore, this energy carrier is way to valuable to use as heat production technology and a function as backup energy is more likely. Heat supply by phase changing materials is still in a development stage. Although, it is unlikely that implementing this technology in the current DHN system is feasible. This technology has the advantage to be very flexible. However,the discharge temperature is not high enough to be useful for the end users. Also, no noticeable environmental improvements will be made when using current transporting vessels.

Focusing on the second sub-question, it can be obtained that especially in the abiotic depletion and global warming impact categories, significant improvements can be made. Improvements on the acidification and photochemical technology seems more challenging. The alternatives leading to the highest environmental improvements are biogas, and hydrogen energy generation. However, it is unlikely that hydrogen will contain a large share in the thermal energy contribution because the current inefficient production methods. This technology could be valuable in the future, if production methods improve. Also, the challenges relating the biogas production quantities makes it unlikely that this technology will have a large contribution at short notice. Therefore, the technologies geothermal and biomass, followed by biogas at an appropriate distance are technologies with the potential to reduce the environmental impact of the thermal energy production.

Chapter 6

Thermal energy configurations

6.1 Proposed energy suppliers

Due to the growing concerns of climate change, and the subsequent policies aiming to shift towards renewable energy systems, the current configuration of thermal energy supply will change (Ministry of Economic Affairs, 2016, p. 40). When changing to a composition of renewable energy, two options can occur. Either the excising power plants will be transformed to more sustainable ones, or new installations will be developed (Blok, 2017). The selection of best suited technologies to replace the present configuration depend, among others, on the available sources and the supply potentials of renewable energy carriers. To serve the ambitious targets of the municipality of Amsterdam a sustainable energy configuration implementation strategy need to be outlined.

Therefore, this chapter focus on the reduction of environmental impacts of various thermal energy supply configurations. This is done based on three proposed energy configurations; BAU, Realistic and Optimistic. The configurations are compiled based on an explorative research, performed in chapter 5. Furthermore, this chapter will give insight, to what extent potential improvements will lead to a reduction of the environmental impact. The environmental impacts assessed for each configuration is compiled using the LCA data from the aforementioned technological improvements, described in chapter 5. However, due to the lack of quantitative data on the annual emissions of PCM, this technology is excluded from the proposed configurations.

The proposed configurations will supply the base load energy, required by the end users. For comparison reasons, the environmental impact assessment of the proposed configurations will use the same DHN connection rate, and direct energy input of the DHN as stated in the baseline year. Only the share of the energy contribution will shift. Determining the capacities required for new proposed technologies is based on the final energy supply of the DHN. Strategies mentioned by the policy makers, together with the current stage of the technologies, are accompanying when composing the sustainability configurations. Aim of the configurations are to achieve a maximum environmental improvement, with minimum infrastructural changes. Focus of the environmental improvements will be on the KPIs selected in chapter 4. The contributions of the proposed technologies per configuration is discussed in section 6.3. The resulting contribution per technology is besides listed in Table 6.1

In the sections that describe the configurations, it will be mentioned how the shifts in technological compositions can be realized. However, it should be noted that the proposed technology shifts are not compulsory, and do not guarantee that the lowest environmental impacts will be reached by using this configurations. Nonetheless, comparing the different configurations with the baseline year of 2015 will give valuable information on the potential environmental improvements that can be reached.

6.1.1 Current situation

The current configuration of the thermal energy supply in the AMA exists mostly out of supply from natural gas. This energy carrier are followed by waste incineration, biomass, geothermal, and biogas with only a little contribution. All technologies, except geothermal energy, are co-generating power plants. Most important energy carrier is natural gas. Although natural gas is a relatively clean fossil fuel energy source, it has poor performance on the depletion of abiotic resources and CO_2 emissions, and need to be replaced by renewable sustainable sources (Shahidehpour, Fu, and Wiedman, 2005, p. 1053). Most polluting energy source in the energy configuration is waste incineration, especially when this technology replaces the recycling of waste (Eriksson et al., 2007, p. 1357). Besides the relatively high emissions occurring from the combustion of waste, it has to be shipped from other countries to reach the demand. The remaining sustainable sources account for a small share but can result in significant improvements concerning climate change.

6.1.2 BAU configuration

In the BAU configuration there will be no changes in technology configurations, only the share per technology is changed. The primary change relating the current baseline configuration, is the relative large reduction of natural gas. Additionally, the use of waste incineration is eliminated. This is done due the relative high emissions originating from the combustion of waste. The sustainable technologies will gain ground with respect to natural gas combustion. The energy contribution of the technologies is reordered to 70% natural gas. Geothermal, biomass and biogas are responsible for the remaining share, and are equally spread among each other.

In this configuration, the thermal energy delivered by natural gas is still produced by the Diemen 33 and 34 power plants. The total installed capacity of geothermal has to be increased. Adding a new geothermal installation, with a capacity of 34 MW_t, is sufficient to foresee the new demand. The thermal energy produced by AEB with biogas, currently only reaches to 0.08 PJ. Therefore, Almere-1 and Almere-2 will be used to increase the thermal energy generation to the capacity required. The thermal capacities that potentially can be used by co-generation of these plants, are estimated based on the total capacities, given in Table 5.3. This lead to a thermal capacity of respectively 45 MW_t and 35MW_t, assuming a thermal capacity of 40% relative to the total capacities of the plants. This is sufficient to serve the thermal energy required. The energy delivered by biomass from the power plants in Lelystad and Purmerend is, combined, 1 PJ per year. Therefore, this capacity need to be doubled by the development of two similar biomass plants.

6.1.3 Realistic configuration

The implementation of the realistic configuration goes along with ambitious changes and developments of the currently used technologies. No new technologies will be implemented. The most significant change within this configuration are the thermal energy increases of geothermal energy applications and biomass combustion. The shares of the proposed technology configuration consists of 45% natural gas supply, which will remain the biggest thermal energy supplier. Geothermal energy and biomass will come next and are both responsible for an equal thermal energy supply of 20%. Those technologies are shortly followed by biogas with a share of 15%. Translating the shares to the annual final energy shares lead to respectively 9.7, 3.9, 3.9 and 2.9 PJ.

In this configuration, new heat producing technologies need to be developed. This means that geothermal aquifers have to be drilled, to reach the energy required. Three new geothermal wells, each with a capacity of 34 MW_t, need to be developed. Together with the current installed capacity this will lead to an annual energy capacity of 4.7 PJ, sufficient to serve the energy required. Also for the biomass energy generation new power plants need to be developed. Therefore, in order to realize the annual energy production proposed, the development of a biomass power plant with a thermal capacity of at least 92 MW_t is required. The production of the heat requirements of biogas could be achieved by shifting the fuel used by Diemen 33 to biogas. The annual heat production on full capacity of Diemen 33 is 5.7 PJ. Therefore, an operation factor of approximately 50% per year is needed to generate the heat required. The remaining energy required by natural gas can still be reached, using the Diemen 34 power plant, combined with the gas turbines from the VU hospital.

6.1.4 Optimistic configuration

The optimistic thermal energy configuration is composed in such way, that most of the excising infrastructure can be maintained. Next to conserving the infrastructure this configuration strives to accomplish the highest environmental improvements. Therefore, adjustments of power plans and renovation of excising plants lead to the optimistic thermal energy configuration.

Major sustainability change is the complete phased out of fossil fuels. Additionally, the deployment of biogas in existing power plants lead to a significant change. The thermal energy production covered with biogas will equal 40% of the total energy supply. The power plant suited for this transition is the Diemen 34 plant. The transition of geothermal and biomass energy production will, similar to the realistic composition, contain a share of each 20%. Therefore, the development required for these technologies will be equal to the development proposed in the realistic configuration. New technology constituted in this configuration is hydrogen, covering an ambitious share of 20%. Currently this improvement is an energy carrier, and not energy profitable. It requires more energy to produce the hydrogen, than it can potentially generate. Therefore, using current technologies, it makes more sense to directly use the electricity required for the thermal energy, instead of producing hydrogen. Also, its sustainability depends very much on the method used to produce the hydrogen, in this configuration with electrolysis from sustainable wind energy. However, it could be an interesting source in the future due to the low environmental impacts it involves. Unfortunately, the distribution of hydrogen is not included in this study. Therefore, it is expected that the actual emissions will be higher. The location selected to adjust to hydrogen power production is the Diemen 33 power plant.

TABLE 6.1: Proposed configuration shares of the district heat network suppliers for for a transition towards a more sustainable energy supply.

Improvement configuration	**Technology**	
BAU	Natural gas	70%
	Geothermal	10%
	Biogas	10%
	Biomass	10%
Realistic	Natural gas	45%
	Geothermal	20%
	Biomass	20%
	Biogas	15%
Optimistic	Biogas	40%
	Geothermal	20%
	Biomass	20%
	Hydrogen	20%

6.2 Implementation implications

Changing the thermal energy supply configurations involve challenges and significant costs. Energy has to be distributed from new places, and the current infrastructure must face radical changes when shifting to a new configurations. Therefore, it seems important to maintain the excising infrastructure as much as possible. However, these changes will give significant advantages on the long therm by decreasing the environmental impact.

Most significant change is the phase out of waste incineration. Quitting the combustion of waste can on the short term result in waste surpluses. However, the extra waste required, shipped from other countries, will stop. On the short term this can lead to additional problems such as landfill. However, on the long term this waste can be recycled, instead of "downcycling" by simply burning the materials (McDonough and Braungart, 2010, p. 17).

As mentioned the power plants will be maintained as much as possible. However, adjustments need to be made to make them operational for alternative sustainable fuels. This involves multiple challenges. Besides the high costs, it is not possible to deliver heat or electricity for a uncertain period when renovating a power plant. Alternative generators need to be present to cover the demand required. A changing infrastructure by the development of new power plants also lead to the increase of emissions. These emissions are not included in the environmental impact assessment of the proposed configurations. Considerable hazard when transforming natural gas power plans, and the the excising infrastructure to be suited for hydrogen, is the risk of leakages. This risk is considerably larger when using hydrogen due to the smaller molecules it has (Haeseldonckx and D'haeseleer, 2007, p. 1383).

New sustainable energy sources do not necessarily lead to a desired reduction in all environmental impact categories. Biomass combustion for example causes relative high emissions on the photochemical oxidation category, wile the combustion of biogas entail significant acidification emissions (Booth, 2016, p. 1-2; Whiting and Azapagic, 2014, p. 185). Besides, increasing the use of biomass can induce a trade off relating to the land uses. Increased demand of biomass can also effect the transport distances to supply the biomass, involving additional emissions (Heinimö and Junginger, 2009, p. 2949).

Furthermore, additional to the above mentioned, the shift to renewable sources could cause supply implications. Volumes required to meet the energy productions can exceed the current production rates. Therefore, production methods need to be further developed in order to meet the proposed quantities.

6.3 Environmental improvement

The three configurations composed are compared based on their LCA environmental impact results, computed in chapter 5. The configurations are assessed on their environmental performance in the exact same method as performed in chapter 5. Only the energy share of the compositions are adjusted to the proportions proposed per configuration. The results by the adjustments are compared with the baseline values given in Table 4.2. The amount of final energy use of the gas network, combusted in high efficiency condensing boilers, including the connection ratio of the DHN, are retained in the impact assessment.

The results of the environmental improvements of the given configurations are showed in Figure 6.1. From this figure it can be seen that the contributions of the improvements varies per KPI impact category. All configurations represent improvements relating to the abiotic depletion and global warming potential impact categories. However, due to the use of biogas and biomass, the acidification and photochemical oxidation category show an increasing impact, relative to the baseline year. The lack of improvement in these two impact categories can be explained by the relative clean combustion technologies of natural gas. Therefore, the less natural gas is used per configuration, the higher the impacts on acidification and photochemical oxidation. This can be seen on the results of the realistic and optimistic configurations. Also, due to the fixed share of direct energy input of the DHN, connecting only 11% of the AMA, no significant impact reductions are reached. This is due to the emission that belong to the combustion of natural gas with the high efficiency condensing boilers, that is kept equal to the baseline year 2015 in this assessment.

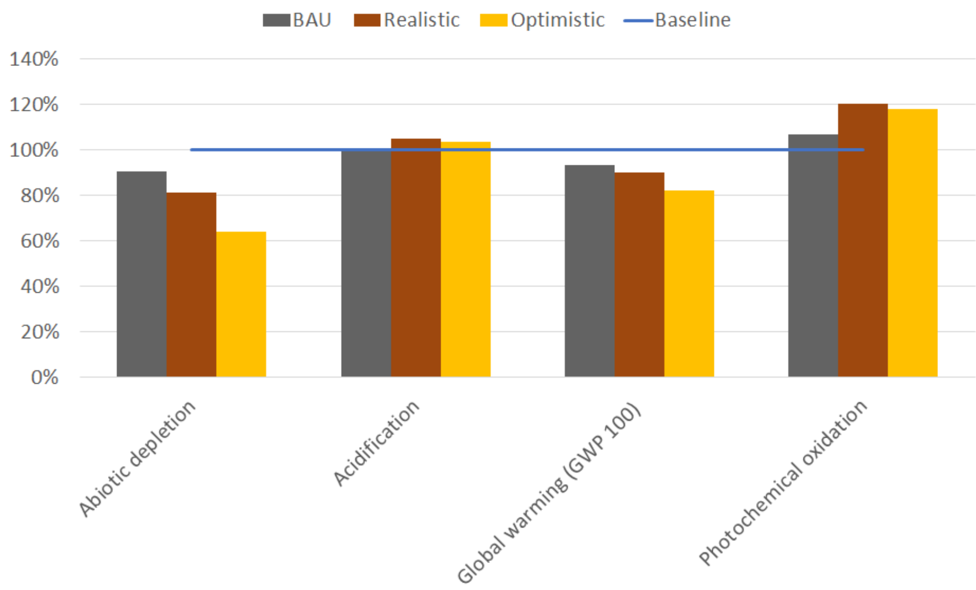

FIGURE 6.1: Environmental performance of the proposed configurations relative to the baseline KPIs. The figure includes the emissions originating from the direct energy input of the natural gas network, combusted in high efficiency condensing boilers, that is kept the same to the baseline year. And the emissions emitted by the direct energy input of the DHN, using the new proposed configurations.

6.4 Sensitivity analyses

To determine which parameters of the technologies used in the proposed configurations have a high influence on the end results, a sensitivity analysis is performed. Each parameter have been adjusted with -50 and +50%, to determine influence on the overall impact. The sensitivity analysis is performed on the parameters:

- Natural gas, combusted in CHP plants
- Geothermal energy
- Biogas
- Biomass
- Hydrogen
- Natural gas, combusted in high efficiency condensing boilers
- Natural gas, production

The results of the sensitivity analysis reveals that the thermal energy supply by the natural gas boilers have a high influence on the overall environmental impact. The results of the sensitivity analysis are showed in Table 6.2 and are presented in percentage of change, relative the the total impact per impact category. Table 6.2 only shows the results of the BAU configuration of the global warming KPI. The sensitivity analysis of all configurations and KPIs are placed in Appendix I

TABLE 6.2: Sensitivity analysis global warming

Improvement configuration	**Technology**	**-50%**	**+50%**
BAU	Natural gas, CHP	-6.2%	6.2%
	Geothermal	-0.3%	0.3%
	Biogas	-0.1%	0.1%
	Biomass	-0.3%	0.3%
	Hydrogen	0,0%	0,0%
	Natural gas, Boiler	-42.4%	42.4%
	Natural gas, production	-0.8%	0.8%

6.5 Thermal energy configurations conclusion

The goal of this chapter is to assess the potential overall environmental improvement of the thermal energy supply in the AMA. By composing different configurations the third sub-question, given in section 1.4, is answered. The third sub-question is stated as follows:

Which thermal energy configurations can best be implemented in the thermal energy facilities of the Amsterdam metropolitan area and serve the sustainability strategy?

To answer this third research sub-question, the environmental performance is assessed on three different configuration scenarios. The focus of the thermal energy configurations is on heat supply technologies, which are connected to the DHN. The proposed configurations have the potential to serve the thermal energy demand, and are based on reasonable scenarios. The proposed configurations are used to reveal the potential reductions for the long-term. The thermal energy supply by waste incineration will be phased out in all configurations. The three configurations assessed are; BAU, Realistic and Optimistic.

The technology shift in the BAU configuration only consists of minor changes. Natural gas from CHP plants will remain the largest, complemented with an equal spread of the geothermal, biomass and biogas processes. The shift will lead to the development of new geothermal installations, the exploitation of Almere 1 and 2 by biomass and a doubling in capacity for biomass by the development of a new plant. The technology shift of the realistic configuration will also contain natural gas in CHP plants. However, the proportion of sustainable fuels is increased with respect to geothermal energy, biomass and biogas. To foresee the required thermal energy, three geothermal aquifers need to be developed. The capacity by biomass need to become four times higher, this can be realized with the development of one large biomass plant. Biogas combustion will occupy the current Diemen 33 power plant. The optimistic configuration contain most changes, natural gas consumption will be phased out. Biogas will become the main energy supplier, followed by geothermal energy and biomass containing equal identical as the realistic configuration. Finally hydrogen is added as sustainable source. However, with the current production methods, this technology is not feasible. To foresee the required capacities biogas will generate thermal energy in the Diemen 34 CHP plant. Hydrogen will occupy the adjusted Diemen 33 plant.

Implementing the technologies in the different configurations may lead to implications concerning the thermal energy supply. The phase out of waste incineration may lead to waste surpluses, that results in landfill. Another technological shift that can lead to implications is the exploitation of hydrogen in power plants. The risk of leakage due to the smaller hydrogen molecules could cause considerable hazards.

Results of the impact assessment on the three different configurations are divergent for each KPI impact category. All configurations achieve improvements on both the abiotic depletion, and global warming impact category. Unfortunately, no improvements are obtained in the acidification and photochemical oxidation category. This can be explained by the relatively low emissions in these two impact categories by the replaced natural gas. The impact assessment includes the the emissions of both the direct energy input of the natural gas network, combusted in high efficiency condensing boilers, and the emissions emitted by the direct energy input of the DHN, that contain the new proposed configurations. Therefore, only limited improvements can be obtained, which can also be verified from the sensitivity analysis. From the results of th sensitivity analysis it can be concluded that natural gas, combusted in high efficiency condensing boilers have the largest influence on the impact outcomes.

In conclusion, the configuration that can best be implemented in the thermal energy facilities of the AMA is the BAU scenario. Especially, if the focus lies on all KPI impact categories. However, since the amount of emissions released by high efficiency condensing boilers is kept the same, no significant improvements are obtained. In addition, the emissions from the high efficiency condensing boilers are relatively high as stated in chapter 4.

Chapter 7

Geo-spatial neighborhood analysis

7.1 District heat network expansion

This chapter will analyze the buildings that potentially can be connected to the DHN, while securing a high efficiency of thermal energy supply. The identification of suited buildings will be performed on neighborhood level.

Before the best suited neighborhoods are identified, aspects relating to the development of the network are investigated. Investigating this progress could give insight on the potential expansion opportunities of the network in the AMA. This aspects will be analyzed based on a qualitative research.

7.1.1 Recent developments of district heat network

In the past years several independent DHNs in the Netherlands are expanding. With data obtained from CBS statline (CBS, 2017a; CBS, 2017d), the development of the total DHN coverage until 2015 is provided (Figure 7.1). The figure shows the percentage of buildings connected in the Netherlands, AMA and Amsterdam, with respect to the total buildings. The overall connection relationship shows an increasing trend. However, a small decrease is seen in the year 2014. This can indicate that more buildings were build, than connected to the grid. Of the urban areas provided, it can be seen that the network expansion of the city Amsterdam spreads the fasted. Reason for this development can be emerged as a result of a rule change in 2014 that stimulates housing corporations to invest in sustainability, and energetically upgrade their housing stocks. This upgrade gives them financial advantages which makes it attractive to connect their properties to the DHNs (Roos and Manussen, 2011, p. 6).

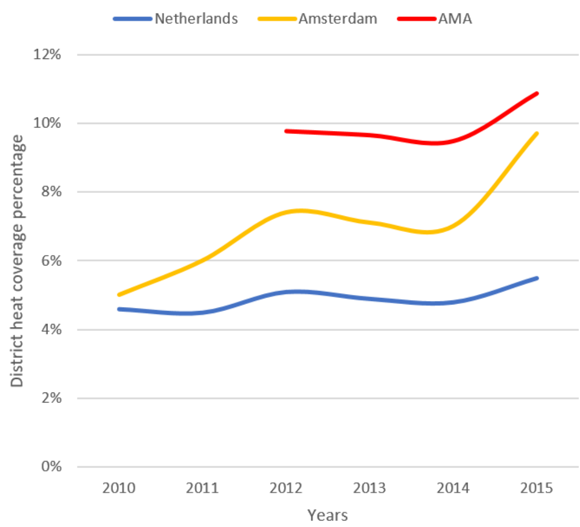

FIGURE 7.1: Total coverage of the district heat network in the Netherlands, Amsterdam metropolitan area and Amsterdam

7.1.2 Policies regarding district heat networks

Policies relating to the heat supply in the Netherlands conduct towards an increasing sustainable energy supply. The Energy agenda (Dutch: Energieagenda) presented by the Minister of Economic Affairs of the Netherlands, Henk Kamp, states that the Dutch Parliament aims to zero CO_2 emissions by the year 2050. To realize this target, a phase-out of natural gas for heating houses will be stimulated (Kamp, 2016, p. 11). Therefore, the regulations that obligates network operators to connect buildings to the gas network will end in 2018 (warmtenetwerk, 2016, p. 7). When these new regulations apply, the DHN will be the prioritized technology to supply heat to the end users. Preferably, the supplied heat originates from residual waste heat of multiple industry sources (Kamp, 2016, p. 53-54).

Also, the municipality of Amsterdam made the development of their DHN as one of the main priorities. Most important policy relating to the heat supply in Amsterdam is adopted in 2006, with motion 838 by Olmer, that stated that new building construction projects will be connected to the DHN, unless analysis turns out that that geographical characteristics are obstructing these possibilities (M. Groot et al., 2008, p. 3). Ambitions of the municipality of Amsterdam relating the development of the DHN are recorded in energy strategy reports. These reports state a connection quantity of 100.000 buildings in 2025, and 200.000 buildings in 2040 (C. C. Leguijt, M. M. Groot, and Bles, 2010, p. 53). The current amount of buildings connected to the DHN reached a extent of approximately 40.000 buildings in 2015.

7.1.3 Alternatives regarding district heat networks

Important consideration when focusing on the expansion of the DHN is the competition between all electric applications, and heating networks. All electric applications is the comprehensive term for solutions such as electric heat pumps and electric boilers, which heat water by running a current to a resistive wire. The latter application could also be integrated in other technologies, e.g. by heating with computing power as heat source. This is an example of a product developed by the Dutch start-up Nerdalize (Strandman et al., 2015, p. 18).

When considering the trade-off between DHN and all electric applications, multiple factors play a role. Most important factor is the cost. These depend on the construction and connection cost of the DHN, including its depreciation and maintenance. The availability of heat sources determine the construction length required to connect the buildings. The cost of all electric applications mostly depend on the invest cost of the individual technologies (Schepers, C. Leguijt, et al., 2015, p. 9). Another factor, is the technical condition of a building. Future low-energy buildings could drastically decrease the heating demand and could therefore be heated by only little support from electrical applications. Connection to a DHN might, for this type of buildings, not be necessary. However, urban areas like the AMA contain many urban areas with old buildings, containing poor isolation standards and high heating demands. Excess heat from industries and power stations, supplied to the buildings with a DHN, can be essential in these areas (Lund et al., 2010, p. 1381). Final factor elaborated is the social resistance against district heat due the high cost relative to natural gas, and the monopoly that arises due to the network ownerships of large single companies (Mulder, Paping, and Huis in ′t Veld, 2014, p. 1-3). The cost of heat supplied by a DHN is adjusted by law, to be equal to natural gas in the "Warmtewet", adopted in January 2014. However, according to Mulder, Paping, and Huis in ′t Veld (2014, p. 2), these costs turn out to be significantly higher. This can be a reason for house owners to prefer all electric applications above DHNs. Therefore, social resistance plays a substantial role in the network expansions.

According to Schepers, C. Leguijt, et al. (2015, p. 8), sparsely populated areas with low heat densities are the best fitted areas to heat using all electric applications. However, this study is based on many assumptions and creates room for debates. According to Lund et al. (2010, p. 1382) there is no single best heating strategy between DHNs and all electric applications. Lund et al. (2010, p. 1389) concludes that the best heating solution is to expand the DHN in urban areas and use electric applications for houses further away.

7.2 Suitable neighborhoods

Within this section the best suited neighborhoods are analyzed. First, it will be determined when neighborhoods are suitable. Based on this result the best fitting neighborhoods are selected in 7.2.2. Subsection 7.2.3 will focus on the distribution and concentrations of the populations in the AMA to determine the best suited neighborhoods. The analysis of the neighborhood identification will be based on a quantitative research.

7.2.1 Specifying suitable

In order to determine when a geographical location is appropriate to be connected to a DHN depends on the heat supplier. To supply heat at a specific location the supplier needs to cover the distribution losses and costs. The lower the distance between the supplier and the consumer, the less the thermal losses and distribution cost. Therefore, DHNs are often located in urban areas with high heat densities (Reidhav and Werner, 2008, p. 867). In urban areas with many attached houses less distribution pipes are required to serve multiple households. Reducing the pipe length increases therefore the efficiency of heat supply. Distributing heat to areas with lower heat densities are less attractive to the heat suppliers and more challenging to connect. In urban neighborhoods with a high heat density, district heating is considered to be profitable. In low heat density neighborhoods alternative sources such as all electric heating is more viable (Persson and Werner, 2011).

Composing the boundary conditions whether the heat density of a neighborhood is high enough to supply heat with a DHN varies per area. Determining this condition depends on two factors; the annual heat demand and the linear heat density. The linear heat density is the annual heat supplied relative to the length of the pipe network (Ahlgren, Simbolotti, and Tosato, 2013, p. 1). According to Ahlgren, Simbolotti, and Tosato (2013, p. 6) and Reidhav and Werner (2008, p. 872) the annual heat demand needs to be at least 50 GJ per building while a linear heat density higher than 2 GJ per meter needs to be reached. The demand values concluded by Reidhav and Werner (2008, p. 872) are based on analysis of houses located in Göteborg, Sweden, which have been connected to a DHN in the past. Different analysis based on multiple projects in Denmark quantified that neighborhoods with an annual heat density of at least 36 MJ/m^2, and a linear heat density of 1.1 GJ per meter should be sufficient to be connected to a DHN (Zinko et al., 2008, p. 2).

7.2.2 Neighborhood identification

As discussed aforementioned, the neighborhoods best fitted to connect to a district network are the particular neighborhoods with a high energy density. Therefore, a quantitative analysis will be performed to determine where these urban areas are located within the AMA. This analysis will be prosecuted with data of the energy consumption within the AMA.
Similar to the spatial analysis in section 4.4 the dataset used only contains the low consuming end users (up to $40m^3/h$). This dataset is obtained from the network operators Alliander and Stedin. The dataset contains the coordinates of aggregated households, which is necessary to perform the spatial joins based on the neighborhood locations. The geographical boundaries of the different neighborhoods is composed by CBS (2015), and will be used to identify the best suited neighborhoods. The heat density of each neighborhood is visualized in MJ/m^2. This makes it possible compare different neighborhoods with each other. The visualizations of the results is obtained by quantitative data mapping, employed with the heat density per neighborhood. All variables are showed by using points with variable sizes, this enables the visualization of the quantitative differences. The larger the sizes the higher the heat density.

Concerning the annual heat demand to be at least 50 GJ per building only a few buildings in some municipalities fail to reach the requirements to be connected to the DHN. As can be obtained from the EFA results of the final energy consumption per building, presented in Appendix E, the total final energy consumption of the municipalities; Beverwijk, Diemen, Edam-Volendam, Haarlemmerliede en Spaarnwoude, Heemskerk, Landsmeer, Ouder-Amstel, Purmerend, Uitgeest and Velsen are not sufficient to meet these requirements.

The results of the spatial analysis in MJ per m^2 is shown in Figure 7.2. In this map all neighborhoods are equipped with quantitative data points, varying in size to indicate how dense each urban area is. The total amount of neighborhoods within the AMA, compared is 1485. Due to this large amount of neighborhoods it can be difficult to identify the value of each neighborhood. However, it can be obtained that most areas containing high heat densities are located in the larger cities. The highest values can be found in the municipalities of Amsterdam, Haarlem, Beverwijk, Gooise meren and Hilversum.

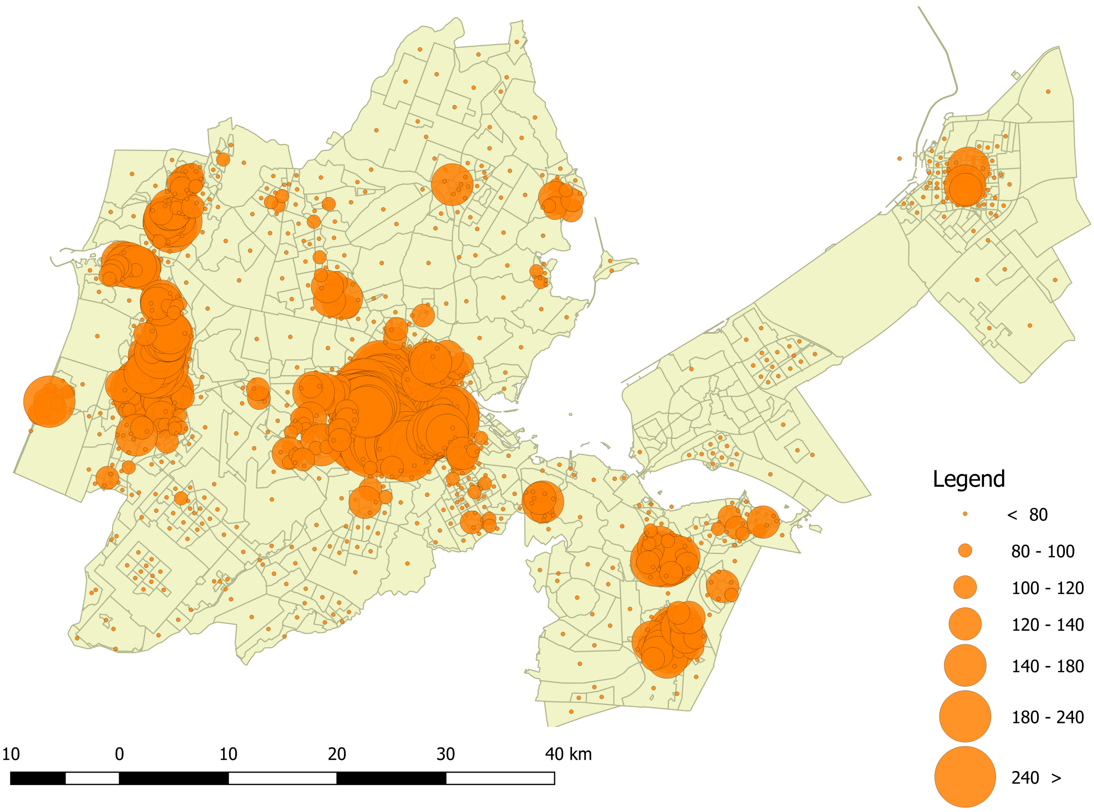

FIGURE 7.2: Heat density of all neighborhoods

In order to accurately identify the order of the highest densities within the distinct neighborhoods, the images 7.3, 7.4, 7.5 and 7.6 below are composed, these figures are also showed in larger sizes in Appendix J. These maps visualize in which order the different heat density values of the neighborhoods are organized. The maps also reveal how the different values spread over the municipalities of the AMA.

The amount of neighborhoods with a heat density higher than 36 MJ/ m^2 equals 834. These neighborhoods together covers 870.374 households, which is 64% of all buildings in the AMA. The total final thermal energy demand of these buildings combined is 43 PJ. Compared to the total amount of neighborhoods this is a significant amount. Reducing this extend can be achieved by considering only the higher energy density neighborhoods. Therefore, the neighborhoods with a heat density of 120 MJ/m^2 or higher are identified. This resulted in 304 suiting, high density neighborhoods, which together covers 352.316 households. This would mean 26% of all buildings located in the AMA. These neighborhoods are listed in Appendix H. The total direct energy demand of the households located within these neighborhoods would equal a total final thermal energy demand of 17 PJ, the results are summarized in Table 7.1.

TABLE 7.1: Heat densities and obtained coverage of suited buildings to be connected to the DHN. Based on the neighborhood identification

Heat density	Number of neighborhoods	Number of buildings	Percentage of buildings	Final energy demand [PJ]
> 36 MJ/m^2	834	870.374	64%	43
> 120 MJ/m^2	304	352.316	26%	17

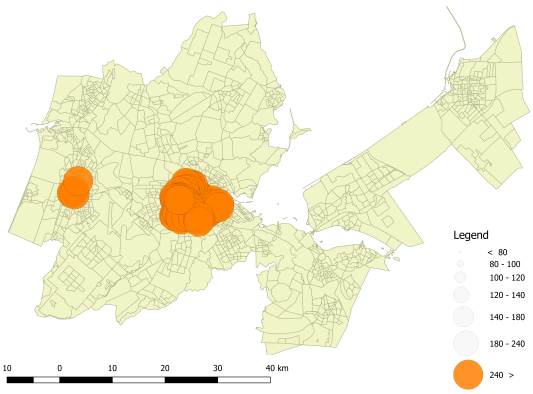

FIGURE 7.3: Heat density neighborhoods, higher than 240 MJ/m^2

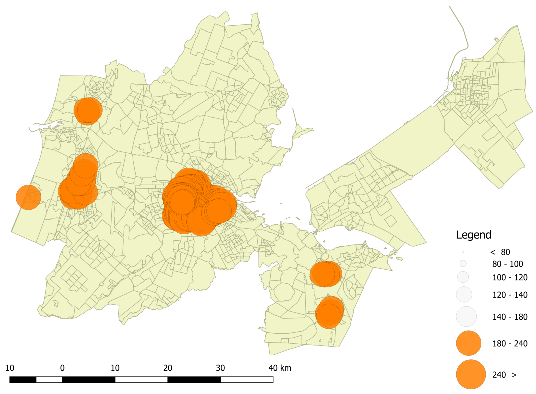

FIGURE 7.4: Heat density neighborhoods, higher than 180 MJ/m^2

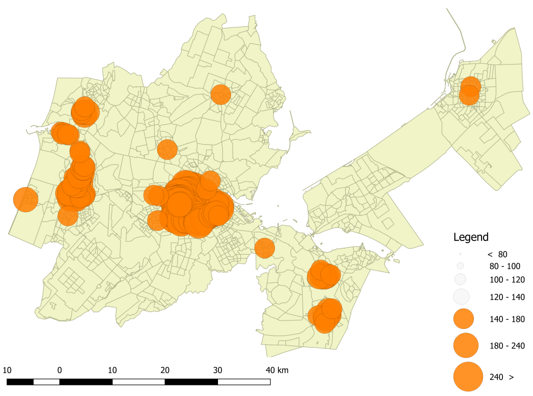

FIGURE 7.5: Heat density neighborhoods, higher than 140 MJ/m^2

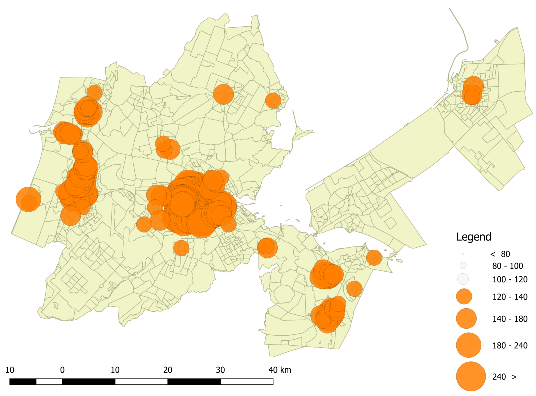

FIGURE 7.6: Heat density neighborhoods, higher than 120 MJ/m^2

7.2.3 Concentrations of demand

The results obtained in previous sections gives valuable information on the locations of the high heat density areas. However, not all neighborhoods contain the same size. Therefore, smaller sized neighborhoods closely located to each other, like for example in Amsterdam and Haarlem, contain less urban land use other than construction areas. This ensures a relatively equal population distribution. Therefore, due to the small neighborhood sizes, these neighborhoods are relatively dense. Larger neighborhoods often contain a variety of land uses e.g. by the parks and lakes they contain. However, the population distribution and concentrations within larger neighborhood can still lead to high heat densities. Also, these neighborhoods can potentially reach a sufficiently high DHN connection density.

Locating the high concentration areas in the AMA is obtained by performing a spatial analysis on the dataset. This is done by clustering the aggregated building data points closely located to each other. This cluster of data points is obtained by placing a distance buffer with a diameter of 150 meters around each point. The buffers created are subsequently dissolved with each other, this creates a cluster of data points which lie within 150 meter from each other. A diameter of 150 meters is selected because every data point represent a minimum of at least 10 unique households. Therefore, the distance between each household in a cluster is relatively low. Every cluster containing less than 10 data points are removed from the dataset to avoid outlying values. The result of the clusters are showed in Figure 7.7. The clusters presented in this figure the are graduated using a color ramp, based on the heat densities between each cluster. Thus, it can be concluded that the cluster covering the neighborhoods of Amsterdam contain the highest heat density.

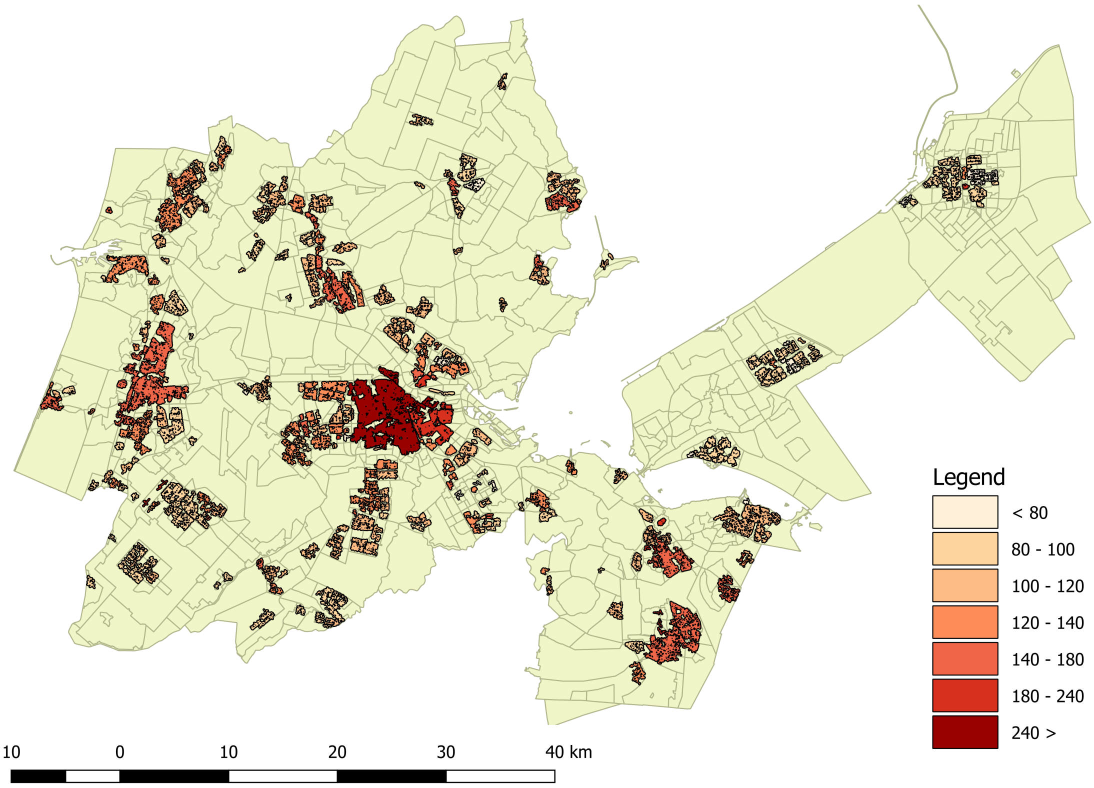

FIGURE 7.7: Distribution of high population concentration areas within the AMA

Similar to the maps in subsection 7.2.2, the results of the the heat densities, per population concentration clusters, are visualized with quantitative data mapping. The results of the spatial analysis are presented in MJ per m^2.

To accurately identify the order of the highest densities within the population clusters, the images 7.3, 7.4, 7.5 and 7.6 below are composed, these figures are also showed in larger sizes in Appendix J. The amount of households located within the created population clusters with a heat density higher than 36 MJ/ m^2 covers 905.827 households, which is higher than the number reached in the neighborhood identification. This represents 67% of all buildings in the AMA. The total final thermal energy demand of these households would altogether reach 44 PJ. When shifting the heat density to 120 MJ/m^2 or higher, 572.141 households are identified to be suitable to connect to the district heat network, equal to 42% of all building in the AMA. The total final thermal energy demand reached by these households would altogether equal 29 PJ, the results are summarized in Table 7.2. Comparing the maps and results of the clusters created with the findings of the neighborhood analysis, it can be seen that the suited locations, containing a high heat density varies in both analysis. Only the urban areas of the municipality Amsterdam happen to contain stable values with high heat densities in both methods. The potential DHN connection densities are higher when analyzing the heat densities of the population concentrations, this is because only construction areas are considered with this method. The areas containing the highest heat densities with the clustering method are in the municipalities of Amsterdam, Hoofddorp, Gooise meren, Hilversum, Lelystad. However, the areas containing high heat densities based on the clustering method are more distributes among the AMA.

TABLE 7.2: Heat densities and obtained coverage of suited buildings to be connected to the DHN. Based on the clustered areas

Heat density	Number of buildings	Percentage of buildings	Final energy demand [PJ]
> 36 MJ/m^2	905.827	67%	44
> 120 MJ/m^2	572.141	42%	29

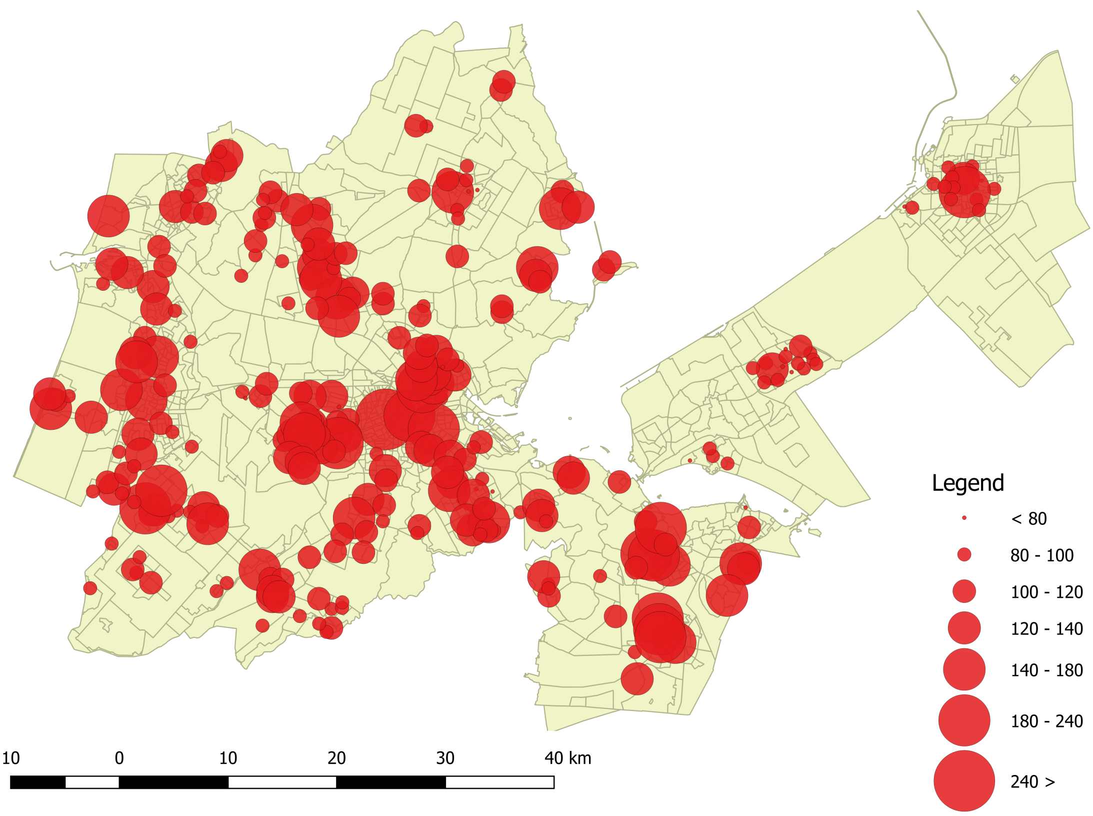

FIGURE 7.8: Heat density of high population concentration areas

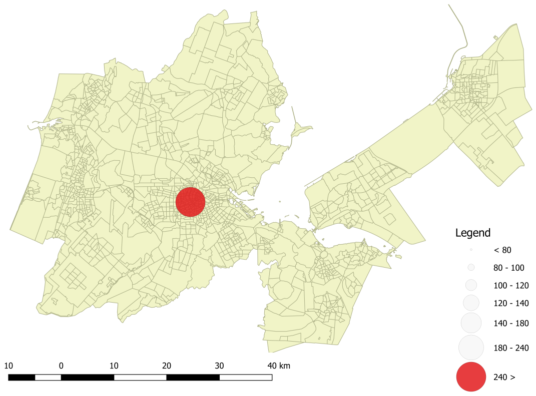

FIGURE 7.9: Heat density of high population concentration areas, higher than 240 MJ/m^2

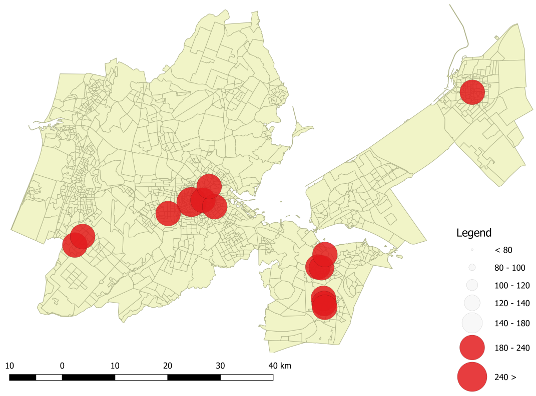

FIGURE 7.10: Heat density of high population concentration areas, higher than 180 MJ/m^2

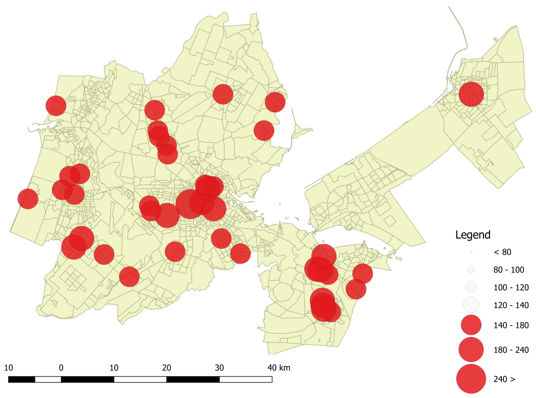

FIGURE 7.11: Heat density of high population concentration areas, higher than 140 MJ/m^2

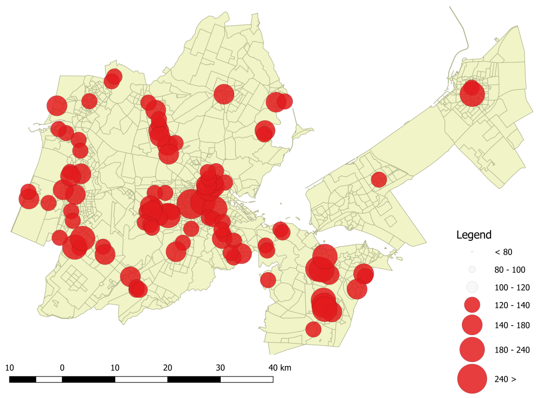

FIGURE 7.12: Heat density of high population concentration areas, higher than 120 MJ/m^2

7.3 Potential environmental improvements

Connecting the identified neighborhoods from the spatial analysis can potentially lead to considerable environmental impact savings.From the analysis of the heat densities of the different neighborhoods, and clustered areas it could be obtained that respectively 26 and 42 percent of the buildings in the AMA contain head densities higher than 120 MJ/m^2. Buildings located in these high thermal energy density areas have a high potential to be connected to a DHN. Therefore, potential environmental impact reductions of an expanded DHN will be assessed in this section. The spatial analysis on the clustered areas showed that 42% contained heat densities higher than 120 MJ/m^2. However, it is not likely that 42% of all building will be connected to the DHN. Besides the municipality of Amsterdam have the ambition to connect a quantity of 100.000 buildings in 2025, and 200.000 buildings in 2040 (C. C. Leguijt, M. M. Groot, and Bles, 2010, p. 53). Therefore, a connection rate of 26% for the entire AMA, equaling approximately 350.000 buildings, seems more plausible in the near future. Subsequently, the potential environmental improvement of an extended DHN to 26 percent will be compared to the baseline situation of 2015.

The energy flow analysis in chapter 3 exposed that too much thermal energy was produced, especially by the Diemen 33 and 34 power plant. From data validation preformed in section 3.4 is could be concluded that an expansion of the DHN is feasible. Also when criticize the final energy produced in the DHN it can be concluded that an extension is possible. Assuming an annual energy consumption of 50 GJ per household it can be obtained that 362.000 buildings could be supplied by the 18.11 PJ final energy of the DHN. This is more than the proposed 26%. Therefore it is assumed that the direct energy input of the DHN can provide the energy required when extended to a connection rate of 26%. The direct energy input of the natural gas network, consumed by high efficiency condensing boilers will decrease to 68.1 PJ due to the decreasing number of gas consumers. Combined with the direct energy input of the DHN and the proposed thermal energy configurations this will lead to a environmental performance on the KPIs as showed in Figure 7.13.

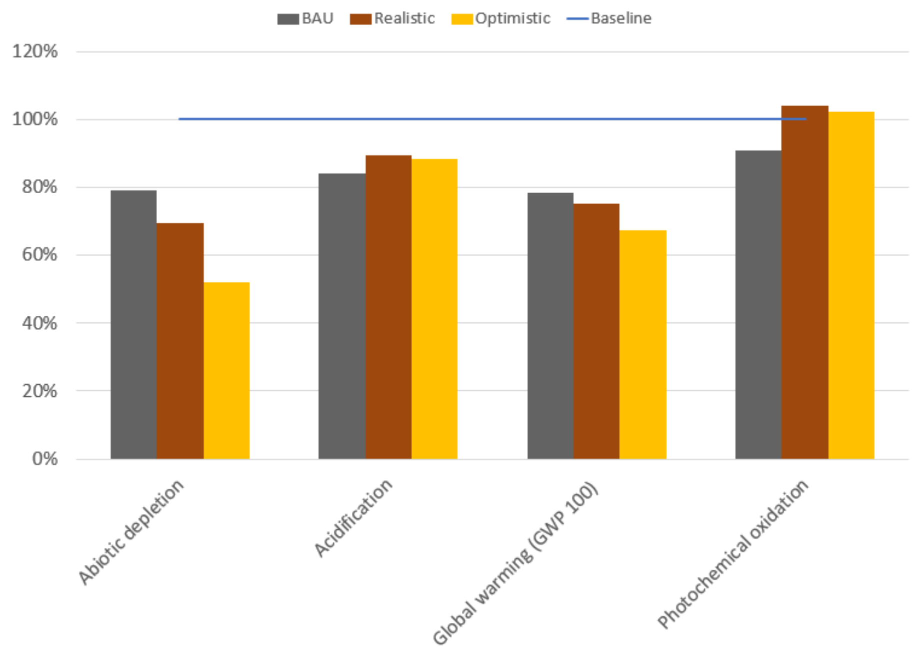

FIGURE 7.13: Potential environmental performance of the proposed configurations relative to the baseline KPIs with a connection rate of 26%

As can be seen in the figure there will only be an significant environmental improvement on the abiotic depletion and global warming potential impact categories for all configurations. Also a considerable improvement is made in the acidification category. The only category that preform worse than the baseline configuration is the photochemical oxidation category belonging to the realistic and optimistic configuration. These configuration emit a little more than the baseline due to the increasing share of the biomass technology.

7.4 Geo-spatial neighborhood analysis conclusion

The goal of this chapter is to analyze the best suited neighborhoods to connect to the district heat network. By analyzing the heat densities the fourth and final sub-question, given in section 1.4, is answered. The fourth sub-question is stated as follows:

Which buildings need to be connected to the district heat network to reach the most efficient thermal energy supply in the Amsterdam metropolitan area?

To answer this sub-question, the suitability of all neighborhoods in the AMA is determined. This is done based on their heat densities. Besides that, locations with high population concentration areas are identified.

The analysis on the expansion of different DHNs in the Netherlands reveals an increasing expansion trend. The reason for this expansion trend can be explained by recent adopted policies in advantage to DHNs. The policy stimulates housing corporations to invest in sustainable adjustments of their housing stocks.

Some municipalities contain an annual heat demand that is not suitable for a DHN connection. These are the municipalities; Beverwijk, Diemen, Edam-Volendam, Haarlemmerliede en Spaarnwoude, Heemskerk, Landsmeer, Ouder-Amstel, Purmerend, Uitgeest and Velsen.

The spatial analysis indicates that areas that often contain convenient heat density characteristics, are areas that are located in or near larger cities. Based on the neighborhood analysis the areas containing the highest values can be found in the municipalities of Amsterdam, Haarlem, Beverwijk, Gooise Meren and Hilversum. However, there are many neighborhoods that have heat densities appropriate for a connection to the DHN. When the heat density requirements were followed, then half of the AMA could be connected to the DHN. Therefore, also a higher energy density is considered. This leads to a distribution of 26% of all buildings located in the AMA, together responsible for a final thermal energy demand of 17 PJ for neighborhoods with an energy density of 120 MJ/m^2 or higher.

A spatial analysis on clustered areas with high population densities reveals even better distribution possibilities. The highest heat densities are found in municipalities of Amsterdam, Hoofddorp, Gooise Meren, Hilversum, Lelystad. The clustered data contains only the buildings located close to each other and states a distribution possibility of 42% for all buildings. Hence, these building requisite a final thermal energy demand of 44 PJ. Also a heat density of 120 MJ/m^2 or higher is used for these clustered areas.

The environmental impact will be reduced when the distribution of 26% suited buildings are actually connected to the DHN. Especially the abiotic depletion and global warming potential impact categories will be lower. The only category that shows a small increase is the photochemical oxidation category. This increase occurs caused by the increasing share of the biomass technology.

In conclusion, the buildings that are located in or near Amsterdam, Hoofddorp, Gooise meren, Hilversum, Lelystad are the buildings that need to be connected to the district heat network. The analysis that is based on the clustering method is more suitable because it only considers the densely populated area. The percentage of 42% of all buildings that are suitable seems a high value, considering that a percentage of 26% will already lead to significant environmental reductions.

Conclusion

This chapter describes all important findings followed from the analysis. It is structured in such a way that all conclusions in the different chapters are discussed. Firstly, the most relevant results are indicated using the energy flow analysis. Secondly, the outcomes of the impact assessment are explained with the corresponding conclusions. Then, possible improvements for further research using different technologies are discussed. The chapter ends with the conclusions from the configurations, followed by the neighborhood analysis.

Energy Flow Analysis

The results of the thermal energy consumption, followed from the energy flow analysis, reveal that the largest part of the direct energy is imported by the municipality of Amsterdam, with an amount of 27.3 PJ. Amsterdam stands out from the rest of the municipalities because it accommodates most of the companies. Hence, approximately 39% of all sectoral and residential buildings of the metropolitan area are located in Amsterdam. The second municipality is Zaanstad importing 8.1 PJ of natural gas. Zaanstad has a high energy import because of the presence of a large manufacturing sector. The third municipality is the Haarlemmermeer with 6.6 PJ. This municipality scores high on the agriculture and retail sectors, which includes transport and storage. This can be explained by the presence of the Amsterdam airport. Five main sectors can be identified, only focusing on the aggregated sectors. The five largest energy importing sectors are agriculture, manufacturing, retail trade, public administration and the residential sector. The high ascendancy of the residential sector is recognizable. The high amount of thermal energy import of the residential sector is related to the dominance of the buildings compared to the remaining sectors. Of all buildings, 82% belongs to the residential sector, together importing 41.4 PJ annually. Another remarkable finding is that the agriculture sector mostly consists out of: Aalsmeer, Almere, Amstelveen, Haarlemmermeer and Uithoorn, together occupying 92.5% of the gas imports in the AMA. All energy imports by the natural gas network results in an energy quantity of 83,7 PJ, that accounts for the direct energy input. In other words, this equals 2.4 billion m^3 natural gas consumption by the high efficiency gas boilers. The total final energy use of the AMA reaches 75.3 PJ. This is the thermal energy that is required to heat the spaces and tap water for the buildings. The remaining 8.4 PJ is lost, caused by conversion of the primary direct energy.

The outcomes of the energy flow analysis, focusing on the district heat network (DHN) supply processes, indicate that multiple energy carriers were used to deliver thermal energy to the connected buildings. Most energy is imported through gas pipelines transporting natural gas from Groningen. The second largest imported energy source is industrial waste, used by the waste to energy (WtE) power plant AEB. The industrial waste import is coming from Great Britain. A total of 207.000 ton, equaling 0.75 PJ, of waste was imported in 2015. This is only a part of the total waste combusted by the AEB WtE power plant. The remaining industrial waste is recycled within the Netherlands and is indicated as domestic extraction. Next to industrial waste, also the energy carriers biomass, biogas and geothermal excess the AMA by domestic extraction. The distribution of energy carriers delivering heat to the district heat network consist of 89.9% natural gas, 5.9% waste incineration, 2.7% biomass, 1.1% geothermal and 0.4% biogas. This distribution is based on the direct energy input of the DHN in the urban metropolitan. The energy carriers which generate heat for the district heat network are produced by eleven different power generators, located in eight different locations. The biggest thermal energy suppliers are Diemen 33 and 34 serving 86% of the direct energy input of the DHN. The total direct energy input of the district heat network reaches 78.8 PJ. 23% of this direct energy input, equaling 18.1 PJ, is delivered to the connected households as final energy. The remaining energy should be considered as a loss, from a thermal energy supply perspective, and attains the value 60.7 PJ. Of the lost energy, 26.5 PJ is converted into useful electrical energy.

Adding both thermal energy supply processes gives a sum of 162.5 PJ direct energy input. Of this amount 93.4 PJ could be used as final energy. Based on the final energy consumption an average annual consumption of 68.8 GJ per year per household is reached. However, from the results it could be deduced that too much energy is produced by the Diemen 33 and 34 power plants. This indicates that not all thermal energy produced by Diemen 33 and 34 is delivered to the district heat network based on the Dutch average annual consumption rates. Hence, a heat network extension is possible considering their thermal capacities. Combining the energy source contribution of the two supplying methods gives a share of 95.1% natural gas, and 2.9, 1.3, 0.5 and 0.2 percent of waste, biomass, geothermal and biogas respectively based on the direct energy inputs. Therefore, it is concluded that the heat supply particularly depends on natural gas.

Impact assessment

The direct energy input, obtained with the EFA, is translated to the amount of emissions emitted in ten different impact categories, performing an impact assessment on the thermal energy supply processes. These results are disposed by both the emission distribution, given per MJ energy input, and the total emissions emitted based on the total direct energy input. The results given per MJ energy input indicate that the natural gas production is (almost) fully responsible for the abiotic depletion impact category. A possible explanation for this result is that the production of natural gas is dedicated to the extraction of this fossil fuel. The remaining impact categories expose that waste incineration and natural gas combustion are dominating. This means that these two processes are the most polluting technologies used in the AMA. Waste incineration and natural gas combustion by condensing boilers score especially high for the global warming impact category. Furthermore, the combustion of biomass results in an ascendancy of the photochemical oxidation impact category. Therefore, increasing heat generation by biomass may lead to extra smog. In addition, the total emissions emitted by the processes based on the total direct energy input are evaluated. According to the evaluation, it turns out that the process, describing the emissions emitted by the natural gas in high efficiency condensing boilers, stands out. This process dominates all other impact categories except the abiotic depletion category. In the abiotic depletion impact category more than 50% of the emissions is responsible for the production of natural gas. The domination of natural gas combustion by high efficiency condensing boilers can be explained by the relative high amount of direct energy used by the boilers, combined with the relative high emissions per MJ.

The cumulative emissions, expressed in mass quantities, are computed to compose a baseline with the selected KPIs. For the abiotic depletion, acidification, global warming (GWP 100) and photochemical oxidation impact categories this results in respectively 152.350 (Sb eq.), 7.640 (SO_2 eq.), 7.870.540 (CO_2 eq.) and 860 (C_2H_4 eq.) ton emissions for the baseline year 2015. The results are compared with related emission studies of DHNs in order to validate the outcomes. This validation step is performed by translating the CO_2 emission outcomes to CO_2 per GJ. This gives 75.3 kg CO_2/GJ for the combustion of natural gas with high efficiency condensing boilers, and 19.9 kg CO_2/GJ for the emission emitted by the DHN. Combining these results, i.e. the total thermal energy supply, the average CO_2 emissions are 48.5 kg/GJ. Therefore, it is concluded that the impact assessment results are representative.

High concentration of emissions within the AMA are identified using a spatial analysis. The high concentrations were mainly concentrated around the power plants. The emission concentrations of the KPIs indicate that the Diemen 33 and 34 power plants are strongly represented in every KPI impact category. Both biomass plants located in Lelystad and Purmerend emit relatively low CO_2 emissions in comparison to the other KPIs. Besides that, according to the remaining combustion technologies the biomass plants score low in CO_2 emissions. Biomass combustion is among all the highest polluting processes, focusing on the photochemical oxidation impact category. Waste incineration emits a relatively high amount of acidification emissions and therefore contributes to acid rain. The spatial analysis of the emissions, excluding the power plants, reveals high concentrations of CO_2 emissions in the municipalities Blaricum, Bloemendaal and Hilversum. This is explained due to the fact that these areas contain a relative large number of detached houses, and contain larger living spaces. Therefore these municipalities consume more natural gas, leading to higher CO_2 emissions. Also, the city center area of Amsterdam reveals high CO_2 emissions. This is caused by the age of the buildings and high population concentrations, which have a negative influence on the natural gas consumptions.

Technologies & Improvements

Research on multiple heat production technologies is conducted, to improve the thermal energy supply in the AMA. These technologies have been analyzed on their environmental performance and are compared to the environmental baseline. The assessed production technologies are geothermal energy, biomass, biogas, hydrogen and phase changing materials

The first technology that is investigated is geothermal energy. This technology is an important alternative and has the support of the government. Especially doublet geothermal systems have advantages in the sense of possible properties to be connected to the DHN. The AMA contains multiple suited locations for geothermal energy, which are mainly located in the north of the North sea Canal. The ground temperature of this area is often higher than the average production temperature elsewhere in the Netherlands. The use of geothermal energy sources leads to significant reductions for depletion of *abiotic resources* and CO_2. The least improvement is obtained in the *acidification* category. This is caused by the negative effect that the acidic fluid injections have on the ground materials in the aquifers. Also the production of methane raises doubts on its sustainability. However, it appears that this only lead to limited extra emissions. The thermal energy produced with biomass is considered to be an viable option as heat supplier. The efficiencies of a biomass plant are mainly depending on the type of biomass used, including its moisture content, combined with the temperature of the return water from the DHN. High moisture content and low water temperatures lead to higher efficiencies. Using biomass has a positive effect on the impact categories. Also, for this technology *abiotic depletion* and CO_2 improves the most in the form of gained reductions. However, *photochemical oxidation*, responsible for smog, will increase significantly. In addition, it is important to consider where the biomass comes from.

Biogas is currently yield from sewage treatment plants. It is possible to increase the production of biogas considering the number of sewage plants. However, this increase will only be limited. This energy has similar characteristics as natural gas, and can be used in original gas turbines. In other words, existing infrastructure could be maintained. From the impact assessment it is concluded that biogas employment especially lead to major improvements in *abiotic depletion* and CO_2. However, *acidification* may increase due to the combustion of biogas.

An alternative production technology that could lead to impact reductions is the technology hydrogen. However, with the current production techniques an effective supply of heat is not feasible. Hydrogen produced with electrolysis is currently the most viable. However, in this state, the technique requires more electrical energy than hydrogen could potentially produce. Therefore, a role as backup energy source seems better suited. Environmental wise, hydrogen reveals significant environmental improvements for all impact categories. However, this depends mostly on the origin of the used electrical energy.

The final energy production technology that is considered is heat derived from phase changing materials. It is concluded that, although the advantages it has, it will not be feasible to implement this technology in the current DHN system. The discharge temperature is too low to be useful for the end users. Besides that, the amount of energy that can be delivered at once is relatively low. Therefore, phase changing materials are unlikely to gain a large share in the heat supply configurations. There are no noticeable environmental improvements obtained with the current transporting techniques.

Configurations

Research on the different configurations is performed to analyze the environmental effect of alternative suppling methods. In the current configuration, natural gas from CHP plants is dominating, concerning the thermal energy supply technologies in the DHN. Alternatives will gain ground in the thermal energy configuration, because this fuel is not sustainable.

Three configurations are assessed on their environmental performance. These configurations are; BAU, Realistic and Optimistic. BAU exists of thermal energy generation techniques producing energy from natural gas, geothermal energy, biomass and biogas. The realistic configuration considers the same technologies. The optimistic configuration will produce thermal energy using biogas, geothermal energy, biomass and hydrogen.

The results of the impact assessment of the configurations diverge for each KPI impact category. However, all configurations achieve improvements for both the abiotic depletion and global warming impact category. Unfortunately, no improvements are obtained in the acidification and photochemical oxidation category. BAU performs best among all impact categories, which may be explained by the relatively low amount of produced emissions by natural gas in the acidification and photochemical oxidation impact category. The results show that the smaller amount of natural gas that is used per configuration, the higher the impacts on acidification and photochemical oxidation are. This is clearly shown by the results of the realistic and optimistic configurations. These configurations contain limited or no natural gas. A fixed share of direct energy input of the DHN and natural gas networks, equal to the baseline year, are used as a comparison. Then, only limited impact reductions are attained.

Neighborhood analysis

The analysis focused on the expansion of different DHNs in the Netherlands reveals an increasing network expansion trend. This because, policies are adopted to the advantage of DHNs. Research to identify new suited locations to connect to the DHN shows that this election mainly depends on the heat densities and annual heat demand per household. Only some municipalities have an inadequate annual heat demand. These are the municipalities; Beverwijk, Diemen, Edam-Volendam, Haarlemmerliede en Spaarnwoude, Heemskerk, Landsmeer, Ouder-Amstel, Purmerend, Uitgeest and Velsen.

Areas that contain high densities are attractive due to the possibility to connect a large number of households, with a relatively low pipe length. Hence, it resulted that urban areas close to larger cities contain more often suited heat density requirements. The cities Amsterdam, Haarlem, Beverwijk, Gooise meren and Hilversum seem to be the best suited neighborhoods considering the heat densities between different neighborhoods. However, many neighborhoods are found to have appropriate heat densities. When sticking to heat density requirements found in literature, more than half of the AMA would qualify to be connected to the DHN. Because of this higher thermal energy densities conditions of 120 MJ/m^2 or higher are used. On this condition a distribution of 26% of all buildings appears to be suitable.

Spatial analysis on clustered areas with high population densities revealed even a higher distribution possibilities. If the analysis is focused on clustered areas, then the cities Amsterdam, Hoofddorp, Gooise meren, Hilversum, Lelystad seem to be best suited areas. Analysis on clustered data containing only buildings located close to each other revealed even a higher distribution possibility. A distribution of 42% of all buildings was reached for a heat density of 120 MJ/m^2 or higher.

Discussion

This discussion chapter elaborates on certain limitations; most of them are based on assumptions that are made for the used methodologies. First the assumptions for the impact assessment methodology are discussed. Then, the issue of data unavailability is explained. Lastly, the necessity of certain decisions are explained with their corresponding effects.

Impact assessment

Conducting a full life-cycle analysis (LCA) could not be performed on the different processes considering the given timescale for this thesis. Existing LCA studies are used, to overcome this problem. However, the methodology is not identical to a complete LCA because not all protocols and guidance relating to the official methodology are pursued. Although a comprehensive approach is maintained, some components belonging to a complete LCA are not considered. Nonetheless, identical LCA software, that is also considered for the associated phases of a full LCA, are combined with comprehensive data obtained from the latest Ecoinvent database.

A relevant note is that the results given by the impact assessment do not represent the exact situation of the current state. The results are considered to be indicative to the reality. In addition, the computed emissions using the database are averages for different processes. Therefore, due to the different simplifications and assumptions the results can deviate from the assessed processes.

A final point that is worth mentioning is related to the allocation factors that are applied for the co-generation techniques. In this study the used factors are based on the economical value of the energy outputs. However, this can lead to emission values that slightly differ from the assessed processes.

Data unavailability

The thermal capacities are required for the analysis of the thermal energy supply of the different power plants that supply the thermal energy to the district heat network. Unfortunately, not all capacities could be obtained. Therefore, maximum capacities are used for some power plants. However, using the maximum capacities lead to different results and can be misleading relative to the actual case. An example of misleading results are the annual final energy consumptions of Almere. These consumptions are three times larger than the Dutch average consumptions.

In addition to the produced thermal capacities no information is given on the actual heat delivery to the DHN. In some cases the thermal capacities are likely to be equal to the delivered heat. However, for other cases it seems more likely that not all produced heat is delivered to the DHN, e.g. the amount of energy still exceeds the plausible thermal delivery quantities, after the adjustment of the thermal energy productions for Diemen 33 and 34.

The data, specific for the different sectors, that is obtained from the CBS is not specific as the data is given on municipality level. A better analysis could be performed if the data is given on sector level.

Furthermore, the data that is used for the spatial analysis of the emitted emissions and the neighborhood identification does not contain the high consuming end users, i.e. consuming more than $40m^3/h$. This leads to an energy gap of 30.1 PJ. Hence, including the high energy consuming data leads to more accurate results.

The problem of data unavailability is encountered during the collection phase of the data for different process, e.g. there was no data available in the Ecoinvent database for the hydrogen and phase changing materials. In the case of hydrogen this gap is filled using literature. However, using data from different sources also means that different assumptions, scopes and approaches are used. This confirms that the results obtained from the impact assessment are indicatively, and do no necessarily imply that the results are exact.

Selection and decisions

Selections on the improvement and technologies are mainly made based on the potential of the environmental improvements. In reality, these selections and decisions are mostly based on the relating costs. This is especially the case for the hydrogen technology. Although this is an expensive technology to use due to the high electric energy requirements, and thus seems to be better suited as backup technology, it performs well on the environmental impact categories.

The key performance indicators are selected based on the sustainable preferences of different municipalities in the research and in consultation with the supervisors. However, it can not be said that the selected impact categories are more important than others. Therefore adding or replacing impact categories could be an interesting recommendation.

Appendix A

Energy Flow Analysis

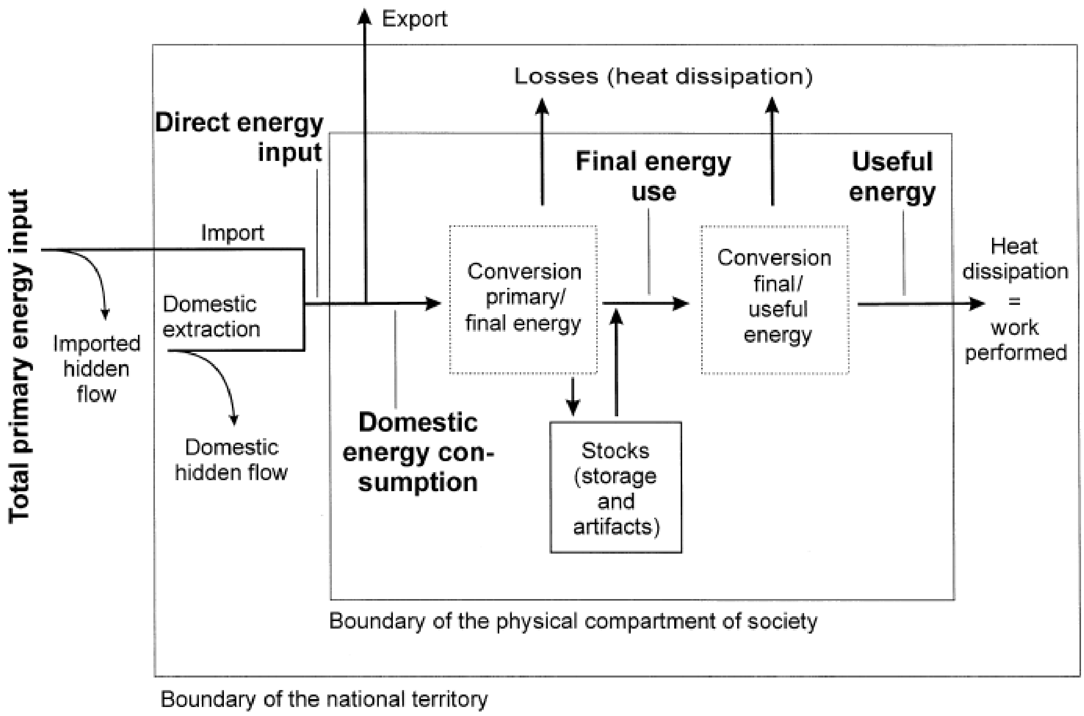

FIGURE A.1: Flow of energy through a society based region (Helmut Haberl, 2001)

Appendix B

Energy content

TABLE B.1: Energy sources and Energy content

Energy source	Explanation	Energy content (GJ)
1 GJ	1 gigajoule (1 billion joule)	1
1 PJ	1 petajoule	1.000.000
1 MWh	1 megawatt hour (1.000 kilowatt hour)	3,6
1000 m^3 gas (Groningen)*	1.000 m^3 Groningen-natural gas eq.at a pressure of 1.01325 bar and 0°C	35.17
1000 m^3 gas (Standard)**	1.000 m^3 natural gas at a pressure of 1.01325 bar and 15°C (ISO-norm)	31.65
1000 m3 biogas	1.000 m^3 biogas at atmospheric pressure	31.65
1 ton mixed logs	1.000 kg mixed logs biomass	18
1 ton municipal solid waste	1.000 kg municipal solid waste	3.62
1 ton hydrogen	1.000 kg hydrogen, at 690 bar and 15°C	141.86

* Energy content used for gas consumed within households using boilers
** Energy content used for gas consumed within power plants

TABLE B.2: Basic unit of measure, metric prefixes

Prefixes	Explanation
kilo (k)	10^3 = 1.000 (= thousand)
mega (M)	10^6 = 1.000.000 (= million)
giga (G)	10^9 = 1.000.000.000 (= billion)
tera (T)	10^{12} = 1.000.000.000.000
peta (P)	10^{15} = 1.000.000.000.000.000

Appendix C

High-level aggregation per municipality

TABLE C.1: Total company establishments and residential buildings per sector

Total company establishments and residential buildings per sector													
Municipality	1	2	3	4	5	6	7	8	9	10	11	12	Total
Aalsmeer	140	5	135	295	965	145	395	75	750	NA	350	12803	16058
Almere	85	30	505	1410	3735	1370	855	185	4145	NA	1865	78974	93159
Amstelveen	80	10	160	370	1620	555	795	215	2445	NA	845	42736	49831
Amsterdam	105	185	2560	4760	22395	10325	7325	2080	35470	NA	20845	416966	523016
Beemster	180	0	45	125	195	30	90	20	225	NA	115	3641	4666
Beverwijk	25	25	135	465	1330	135	245	65	670	NA	375	18760	22230
Blaricum	5	0	35	75	190	70	200	40	405	NA	130	4272	5422
Bloemendaal	10	5	45	125	400	100	450	75	1020	NA	260	9619	12109
Diemen	5	0	65	220	595	165	170	50	630	NA	310	13132	15342
Edam-Volendam	315	50	205	1170	1200	215	515	90	1080	NA	505	14858	20203
Gooise Meren	35	15	195	510	1330	530	825	165	2670	NA	785	26075	33135
Haarlem	20	20	450	1585	3165	1110	1030	250	4940	NA	2265	73230	88065
Haarlemmerliede en Spaarnwoude	15	0	20	95	130	50	65	10	155	NA	90	2276	2906
Haarlemmermeer	360	20	555	1450	4035	815	1495	245	3975	NA	1375	59292	73617
Heemskerk	85	10	95	320	615	130	240	35	590	NA	300	17361	19781
Heemstede	10	0	60	160	565	140	375	70	1050	NA	270	12321	15021
Hilversum	20	5	260	930	1760	1105	730	180	3110	NA	1225	40861	50186
Huizen	20	5	135	490	795	280	465	90	1190	NA	480	18544	22494
Landsmeer	30	0	35	150	250	65	140	30	330	NA	150	4646	5826
Laren (NH.)	5	0	50	90	345	110	280	70	610	NA	165	5167	6892
Lelystad	160	30	275	635	1600	420	350	95	1490	NA	715	32658	38428
Oostzaan	15	0	25	125	200	40	90	15	195	NA	90	3932	4727
Ouder-Amstel	40	5	65	125	385	160	195	45	555	NA	180	5781	7536
Purmerend	5	5	215	630	1460	300	375	90	1235	NA	670	35353	40338
Uitgeest	25	0	65	165	195	50	100	20	270	NA	105	5520	6515
Uithoorn	135	10	100	235	635	140	285	40	655	NA	270	12603	15108
Velsen	35	25	235	780	1220	200	455	85	1280	NA	600	30621	35536
Waterland	100	0	70	175	335	90	150	25	485	NA	235	7228	8893
Weesp	35	5	125	175	470	140	160	40	540	NA	230	8715	10635
Wijdemeren	70	5	155	335	650	195	330	75	870	NA	365	10344	13394
Wormerland	70	0	90	220	230	60	125	30	310	NA	155	6696	7986
Zaanstad	90	25	730	1780	2865	640	820	180	2665	NA	1400	66549	77744
Zandvoort	5	0	45	195	530	90	170	35	450	NA	230	9403	11153
Metropolitan area Amsterdam	2335	495	7940	20370	56390	19970	20290	4815	76460	0	37950	1110937	1357952

TABLE C.2: Direct gas input in m^3 per sector [x1.000.000]

Direct gas input in m^3 per sector [x1.000.000]													
Municipality	1	2	3	4	5	6	7	8	9	10	11	12	Total
Aalsmeer	28.97	0.01	0.60	0.14	3.06	0.07	0.26	0.41	0.21	0.89	0.18	18.05	52.84
Almere	21.47	0.03	5.48	0.34	4.01	0.00	0.25	0.66	0.27	3.75	1.11	34.75	72.12
Amstelveen	16.94	0.41	0.71	0.14	4.13	0.34	1.23	2.94	1.06	6.16	2.11	49.15	85.30
Amsterdam	1.17	6.93	141.98	0.00	80.25	8.48	14.93	0.00	13.95	108.77	21.68	362.76	760.88
Beemster	2.65	0.00	0.00	0.32	0.85	0.01	0.00	0.03	0.03	0.35	0.08	5.86	10.16
Beverwijk	0.03	0.03	1.43	0.31	1.33	0.09	0.23	0.28	0.42	0.68	0.35	22.32	27.50
Blaricum	0.04	0.00	0.08	0.05	0.51	0.06	0.16	0.06	0.20	1.00	0.15	8.54	10.85
Bloemendaal	0.07	0.12	0.07	0.09	1.03	0.10	0.48	0.19	0.57	2.48	0.58	20.68	26.45
Diemen	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.20	0.09	0.04	13.26	13.66
Edam-Volendam	0.26	0.00	0.41	0.09	0.25	0.03	0.13	0.08	0.25	0.17	0.05	23.84	25.57
GooiseMeren	0.22	0.01	3.99	0.19	3.92	1.28	0.92	0.43	1.04	3.89	2.06	44.45	62.39
Haarlem	0.26	0.86	8.65	0.59	13.90	1.26	1.23	1.49	2.80	13.68	3.93	91.54	140.18
Haarlemmerliede en Spaarnwoude	0.01	0.00	0.27	0.09	0.34	0.01	0.04	0.00	0.03	0.20	0.07	3.28	4.34
Haarlemmermeer	46.10	0.26	6.80	1.35	36.96	2.15	1.85	1.99	1.91	8.86	2.99	75.30	186.50
Heemskerk	5.48	0.00	0.19	0.08	1.43	0.01	0.13	0.01	0.17	1.61	0.86	21.18	31.15
Heemstede	0.16	0.12	0.09	0.07	1.54	0.04	0.18	0.20	0.41	2.15	1.18	19.96	26.09
Hilversum	0.03	1.06	1.23	0.33	5.81	7.89	0.99	2.13	1.23	8.33	2.65	59.25	90.93
Huizen	0.02	0.00	4.87	0.18	2.04	0.21	0.25	0.20	0.40	2.36	0.85	26.15	37.51
Landsmeer	0.00	0.00	0.00	0.09	0.09	0.03	0.05	0.02	0.07	0.14	0.10	6.92	7.52
Laren(NH.)	0.03	0.01	0.03	0.02	1.08	0.08	0.29	0.10	0.24	1.30	0.63	11.73	15.55
Lelystad	0.13	0.05	33.28	0.52	7.08	0.00	0.53	0.59	3.08	6.07	1.50	28.09	80.93
Oostzaan	0.01	0.00	1.37	0.06	0.68	0.01	0.02	0.00	0.05	0.16	0.11	5.54	8.01
Ouder-Amstel	0.01	0.10	0.00	0.03	0.00	0.12	0.00	0.00	0.00	0.16	0.07	7.52	8.02
Purmerend	0.00	0.00	0.25	0.09	1.90	0.21	0.11	0.14	0.13	2.03	0.21	12.73	17.79
Uitgeest	0.06	0.00	0.23	0.08	0.86	0.01	0.05	0.01	0.08	0.35	0.22	7.23	9.19
Uithoorn	64.45	0.03	4.38	0.13	1.50	0.06	0.18	0.08	0.19	1.10	0.53	16.01	88.62
Velsen	0.19	0.32	0.00	0.46	9.57	0.16	0.25	0.33	0.43	3.29	1.27	38.89	55.15
Waterland	0.22	0.03	0.35	0.08	1.23	0.05	0.08	0.04	0.12	0.72	0.39	11.13	14.44
Weesp	0.02	0.06	9.93	0.04	1.79	0.05	0.22	0.44	0.12	0.83	0.54	9.94	23.96
Wijdemeren	0.46	0.03	0.37	0.19	1.97	0.07	0.27	0.27	0.24	1.12	2.21	17.58	24.77
Wormerland	0.22	0.00	9.49	0.10	0.65	0.04	0.14	0.02	0.10	1.12	0.29	9.17	21.35
Zaanstad	2.69	0.00	112.52	1.03	14.18	0.37	0.47	0.89	1.17	8.65	3.09	81.86	226.90
Zandvoort	0.00	1.58	0.07	0.05	3.44	0.07	0.00	0.11	0.08	1.38	0.39	12.32	19.48
Metropolitan area Amsterdam	192.35	12.03	349.11	7.32	207.39	23.41	25.89	14.13	31.22	193.84	52.46	1176.97	2286.13

TABLE C.3: Final energy consumption per building user. DHN not included [GJ/year]

Final energy consumption per building user. DHN not included [GJ/year]													
Municipality	1	2	3	4	5	6	7	8	9	10	11	12	Total
Aalsmeer	6.549.9	63.3	139.7	14.8	100.5	14.2	20.8	171.8	8.9	NA	16.1	44.6	104.2
Almere	7.995.2	30.6	343.5	7.5	34.0	NA	9.3	113.4	2.0	NA	18.8	13.9	24.5
Amstelveen	6.702.1	1.300.9	140.5	12.1	80.6	19.2	49.1	432.7	13.7	NA	78.9	36.4	54.2
Amsterdam	351.2	1.185.0	1.755.5	NA	113.4	26.0	64.5	NA	12.4	NA	32.9	27.5	46.0
Beemster	465.5	NA	NA	79.8	138.0	11.6	NA	41.1	3.7	NA	20.9	51.0	68.9
Beverwijk	39.2	38.0	335.3	21.1	31.6	21.8	29.5	135.4	19.9	NA	29.4	37.7	39.2
Blaricum	259.6	NA	72.3	21.9	84.6	26.2	24.5	48.3	15.9	NA	35.8	63.3	63.4
Bloemendaal	215.2	772.3	47.8	22.5	81.7	32.6	33.6	79.8	17.6	NA	70.5	68.1	69.2
Diemen	NA	NA	NA	NA	NA	13.0	NA	NA	10.0	NA	4.0	32.0	28.2
Edam-Volendam	26.4	NA	63.5	2.5	6.6	3.7	7.9	28.8	7.4	NA	3.4	50.8	40.1
Gooise Meren	198.1	16.9	647.0	11.5	93.3	76.7	35.3	82.3	12.3	NA	83.1	54.0	59.6
Haarlem	405.2	1.354.7	608.7	11.8	139.0	35.8	37.8	188.9	17.9	NA	55.0	39.6	50.4
Haarlemmerliede en Spaarnwoude	14.8	NA	421.0	31.0	82.5	7.6	17.0	NA	6.7	NA	26.0	45.6	47.2
Haarlemmermeer	4.052.9	416.2	387.9	29.4	290.0	83.4	39.1	256.8	15.2	NA	68.8	40.2	80.2
Heemskerk	2.040.7	6.3	61.6	7.4	73.5	2.9	16.7	11.8	8.9	NA	91.1	38.6	49.8
Heemstede	497.0	NA	49.6	13.3	86.4	9.0	15.0	89.5	12.3	NA	138.2	51.3	55.0
Hilversum	50.6	6.704.1	150.2	11.1	104.5	226.1	43.1	374.2	12.5	NA	68.4	45.9	57.4
Huizen	28.5	NA	1.141.1	11.6	81.1	23.7	16.7	70.0	10.6	NA	55.9	44.6	52.8
Landsmeer	-	NA	NA	19.6	10.9	16.1	12.2	19.0	7.0	NA	21.9	47.2	40.9
Laren (NH.)	208.9	NA	20.9	8.4	99.4	24.2	33.1	44.3	12.6	NA	120.3	71.9	71.4
Lelystad	26.3	55.9	3.830.9	26.1	140.0	NA	47.8	197.9	65.5	NA	66.3	27.2	66.7
Oostzaan	23.2	NA	1.738.4	15.7	108.3	4.7	5.3	NA	7.8	NA	37.3	44.6	53.6
Ouder-Amstel	9.5	626.7	NA	8.6	NA	23.7	NA	NA	NA	NA	12.5	41.1	33.7
Purmerend	NA	NA	37.0	4.6	41.1	22.1	8.9	48.2	3.4	NA	9.9	11.4	14.0
Uitgeest	79.8	NA	113.0	15.5	139.4	4.4	16.8	17.4	9.4	NA	65.4	41.5	44.6
Uithoorn	15.112.1	82.3	1.386.1	17.2	74.5	12.9	19.5	64.9	9.3	NA	62.1	40.2	185.7
Velsen	173.6	406.4	NA	18.7	248.2	25.5	17.7	121.8	10.5	NA	66.8	40.2	49.1
Waterland	70.6	NA	158.3	14.5	116.5	16.9	15.8	54.4	7.9	NA	53.1	48.7	51.4
Weesp	15.4	348.2	2.513.5	7.2	120.8	10.9	44.3	350.6	6.8	NA	74.0	36.1	71.3
Wijdemeren	206.2	189.9	75.2	17.6	96.1	10.7	25.8	112.3	8.7	NA	191.7	53.8	58.5
Wormerland	98.1	NA	3.338.0	14.7	89.3	19.5	35.2	22.2	10.4	NA	60.0	43.4	84.6
Zaanstad	944.3	NA	4.878.8	18.4	156.7	18.2	18.1	155.6	13.8	NA	69.9	38.9	92.4
Zandvoort	NA	NA	49.2	7.5	205.6	26.0	NA	99.5	5.8	NA	53.3	41.5	55.3
Metropolitan area Amsterdam	2.607.5	769.5	1.391.7	11.4	116.4	37.1	40.4	92.9	12.9	NA	43.8	33.5	55.5

TABLE C.4: Final energy consumption per building user. including DHN [GJ/year]

Final energy consumption per building user. including DHN [GJ/year]													
Municipality	1	2	3	4	5	6	7	8	9	10	11	12	Total
Aalsmeer	6549.9	63.3	139.7	14.8	100.5	14.2	20.8	171.8	8.9	NA	16.1	44.6	104.2
Almere	7995.2	30.6	343.5	7.5	34.0	NA	9.3	113.4	2.0	NA	18.8	122.2	116.3
Amstelveen	6702.1	1300.9	140.5	12.1	80.6	19.2	49.1	432.7	13.7	NA	78.9	49.0	65.0
Amsterdam	351.2	1185.0	1755.5	NA	113.4	26.0	64.5	NA	12.4	NA	32.9	46.4	61.1
Beemster	465.5	NA	NA	79.8	138.0	11.6	NA	41.1	3.7	NA	20.9	51.0	68.9
Beverwijk	39.2	38.0	335.3	21.1	31.6	21.8	29.5	135.4	19.9	NA	29.4	37.7	39.2
Blaricum	259.6	NA	72.3	21.9	84.6	26.2	24.5	48.3	15.9	NA	35.8	63.3	63.4
Bloemendaal	215.2	772.3	47.8	22.5	81.7	32.6	33.6	79.8	17.6	NA	70.5	68.1	69.2
Diemen	NA	NA	NA	NA	NA	13.0	NA	NA	10.0	NA	4.0	42.3	37.1
Edam-Volendam	26.4	NA	63.5	2.5	6.6	3.7	7.9	28.8	7.4	NA	3.4	50.8	40.1
Gooise Meren	198.1	16.9	647.0	11.5	93.3	76.7	35.3	82.3	12.3	NA	83.1	54.0	59.6
Haarlem	405.2	1354.7	608.7	11.8	139.0	35.8	37.8	188.9	17.9	NA	55.0	39.6	50.4
Haarlemmerliede en Spaarnwoude	14.8	NA	421.0	31.0	82.5	7.6	17.0	NA	6.7	NA	26.0	45.6	47.2
Haarlemmermeer	4052.9	416.2	387.9	29.4	290.0	83.4	39.1	256.8	15.2	NA	68.8	40.2	80.2
Heemskerk	2040.7	6.3	61.6	7.4	73.5	2.9	16.7	11.8	8.9	NA	91.1	38.6	49.8
Heemstede	497.0	NA	49.6	13.3	86.4	9.0	15.0	89.5	12.3	NA	138.2	51.3	55.0
Hilversum	50.6	6704.1	150.2	11.1	104.5	226.1	43.1	374.2	12.5	NA	68.4	45.9	57.4
Huizen	28.5	NA	1141.1	11.6	81.1	23.7	16.7	70.0	10.6	NA	55.9	44.6	52.8
Landsmeer	0.0	NA	NA	19.6	10.9	16.1	12.2	19.0	7.0	NA	21.9	47.2	40.9
Laren (NH.)	208.9	NA	20.9	8.4	99.4	24.2	33.1	44.3	12.6	NA	120.3	71.9	71.4
Lelystad	26.3	55.9	3830.9	26.1	140.0	NA	47.8	197.9	65.5	NA	66.3	33.3	71.9
Oostzaan	23.2	NA	1738.4	15.7	108.3	4.7	5.3	NA	7.8	NA	37.3	44.6	53.6
Ouder-Amstel	9.5	626.7	NA	8.6	NA	23.7	NA	NA	NA	NA	12.5	41.1	33.7
Purmerend	NA	NA	37.0	4.6	41.1	22.1	8.9	48.2	3.4	NA	9.9	34.0	33.8
Uitgeest	79.8	NA	113.0	15.5	139.4	4.4	16.8	17.4	9.4	NA	65.4	41.5	44.6
Uithoorn	15112.1	82.3	1386.1	17.2	74.5	12.9	19.5	64.9	9.3	NA	62.1	40.2	185.7
Velsen	173.6	406.4	NA	18.7	248.2	25.5	17.7	121.8	10.5	NA	66.8	40.2	49.1
Waterland	70.6	NA	158.3	14.5	116.5	16.9	15.8	54.4	7.9	NA	53.1	48.7	51.4
Weesp	15.4	348.2	2513.5	7.2	120.8	10.9	44.3	350.6	6.8	NA	74.0	36.1	71.3
Wijdemeren	206.2	189.9	75.2	17.6	96.1	10.7	25.8	112.3	8.7	NA	191.7	53.8	58.5
Wormerland	98.1	NA	3338.0	14.7	89.3	19.5	35.2	22.2	10.4	NA	60.0	43.4	84.6
Zaanstad	944.3	NA	4878.8	18.4	156.7	18.2	18.1	155.6	13.8	NA	69.9	38.9	92.4
Zandvoort	NA	NA	49.2	7.5	205.6	26.0	NA	99.5	5.8	NA	53.3	43.8	57.3
Metropolitan area Amsterdam	2607.5	769.5	1391.7	11.4	116.4	37.1	40.4	92.9	12.9	NA	43.8	49.8	68.8

Appendix D

Impact categories

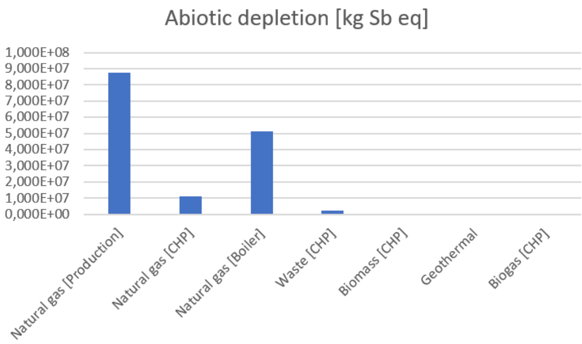

FIGURE D.1: Abiotic depletion

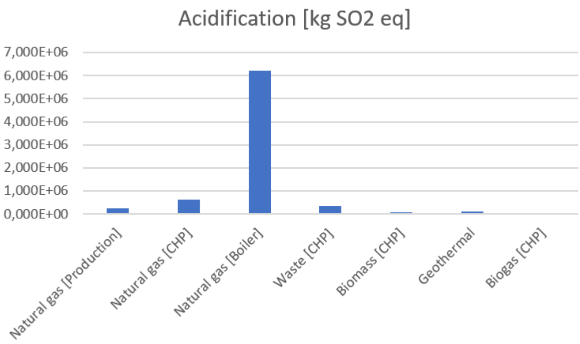

FIGURE D.2: Acidification

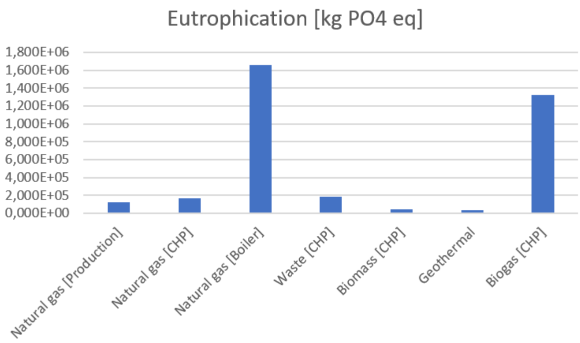

FIGURE D.3: Eutropication

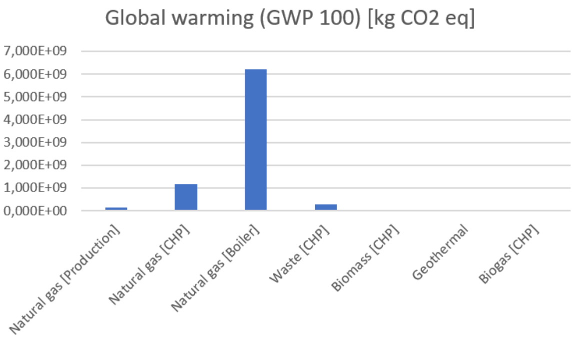

FIGURE D.4: Global warming

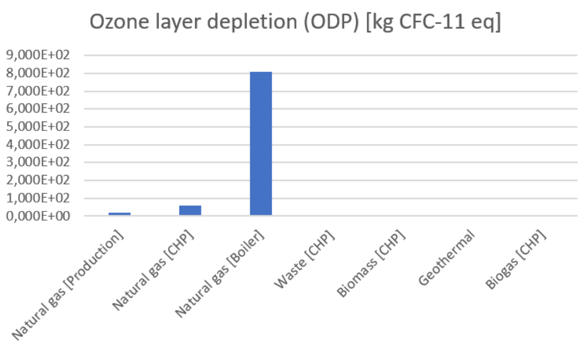

FIGURE D.5: Ozone layer depletion

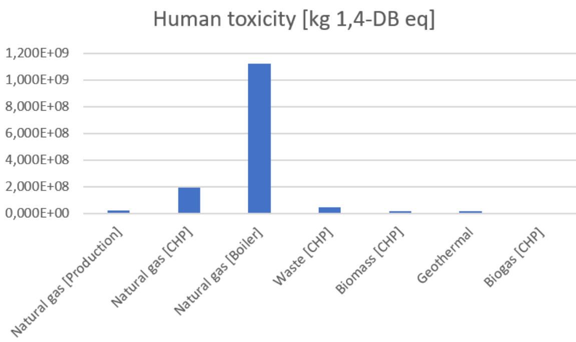

FIGURE D.6: Human toxicity

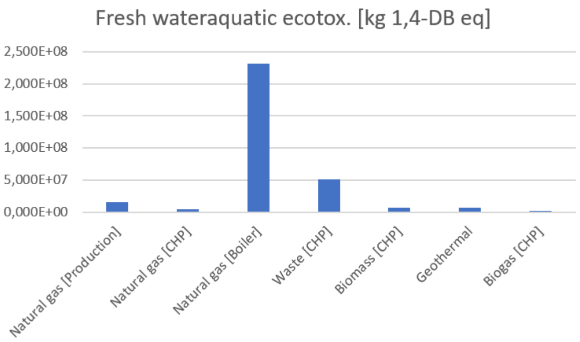

FIGURE D.7: Fresh water-aquatic ecotoxicity

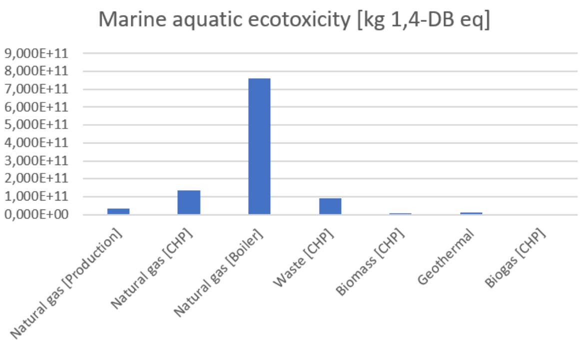

FIGURE D.8: Marine aquatic ecotoxicity

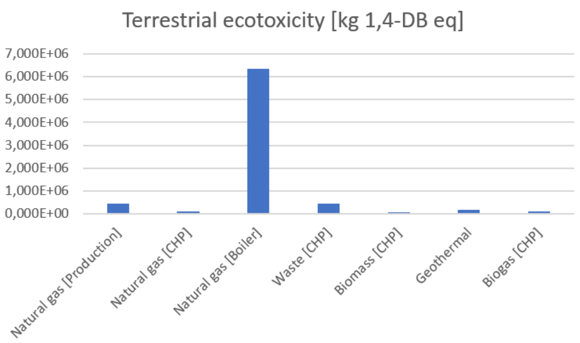

FIGURE D.9: Terrestrial ecotoxicity

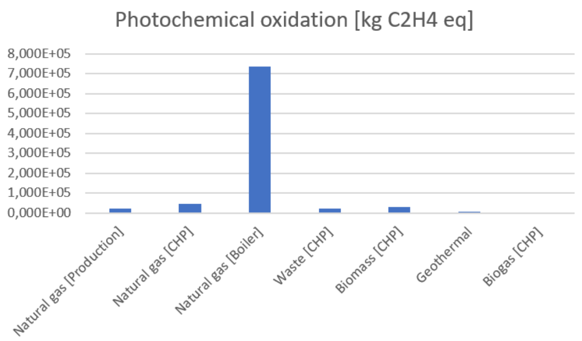

FIGURE D.10: Photochemical oxidation

Appendix E

Network operators and cities of AMA

E.1 Network operator deviation

FIGURE E.1: Deviation of network operators in the Netherlands (Welle Donker, Van Loenen, and Bregt, 2016)

E.2 Cities and towns within AMA

- AALSMEER
- AALSMEERDERBRUG
- ABBENES
- AERDENHOUT
- ALMERE
- AMSTELVEEN
- AMSTERDAM
- AMSTERDAM-DUIVENDRECHT
- ANKEVEEN
- ASSENDELFT
- BADHOEVEDORP
- BEETS NH
- BEINSDORP
- BENNEBROEK
- BENTVELD

- BEVERWIJK
- BLARICUM
- BLOEMENDAAL
- BOESINGHELIEDE
- BREUKELEVEEN
- BROEK IN WATERLAND
- BUITENKAAG
- BURGERVEEN
- BUSSUM
- CRUQUIUS
- DE KWAKEL
- DE NILP
- DIEMEN
- DRIEHUIS NH
- DUIVENDRECHT
- EDAM
- HAARLEM
- HAARLEMMERLIEDE
- HALFWEG NH
- HEEMSKERK
- HEEMSTEDE
- HILVERSUM
- HOBREDE
- HOOFDDORP
- HUIZEN
- IJMUIDEN
- ILPENDAM
- JISP
- KATWOUDE
- KOOG AAN DE ZAAN
- KORTENHOEF
- KROMMENIE
- KUDELSTAART
- KWADIJK
- LANDSMEER
- LAREN NH
- LEIMUIDERBRUG
- LELYSTAD
- LIJNDEN
- LISSERBROEK
- LOOSDRECHT
- MARKEN
- MIDDELIE
- MIDDENBEEMSTER
- MONNICKENDAM
- MUIDEN
- MUIDERBERG
- NAARDEN
- NEDERHORST DEN BERG
- NIEUW-VENNEP
- NOORDBEEMSTER
- OOSTHUIZEN
- OOSTKNOLLENDAM
- OOSTZAAN
- OUDEMEER
- OUDERKERK AAN DE AMSTEL
- OVERVEEN
- PURMER
- PURMEREND
- PURMERLAND
- RIJSENHOUT
- ROZENBURG NH
- SANTPOORT-NOORD
- SANTPOORT-ZUID
- SCHARDAM
- SCHIPHOL
- SCHIPHOL-RIJK
- 'S-GRAVELAND
- SPAARNDAM GEM. HAARLEM
- SPAARNDAM WEST
- SPIJKERBOOR NH
- UITDAM
- UITGEEST
- UITHOORN
- VELSEN-NOORD
- VELSEN-ZUID
- VELSERBROEK
- VIJFHUIZEN
- VOGELENZANG
- VOLENDAM
- WARDER
- WATERGANG
- WEESP
- WESTBEEMSTER
- WESTKNOLLENDAM
- WESTZAAN
- WETERINGBRUG
- WIJDEWORMER
- WIJK AAN ZEE
- WORMER
- WORMERVEER
- ZAANDAM
- ZAANDIJK
- ZANDVOORT
- ZUIDERWOUDE
- ZUIDOOSTBEEMSTER
- ZWAANSHOEK
- ZWANENBURG

Appendix F

Environmental improvement all impact categories

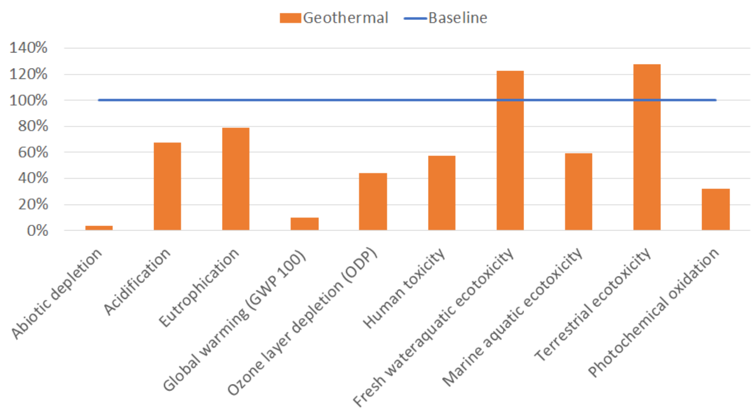

FIGURE F.1: Environmental performance of geothermal energy on the selected KPIs related to the baseline impact in the year 2015

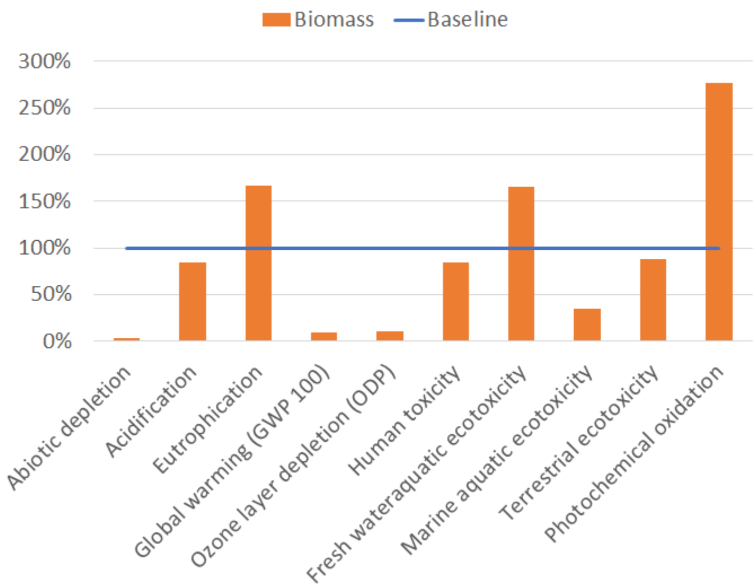

FIGURE F.2: Environmental performance of biomass on the selected KPIs related to the baseline impact in the year 2015

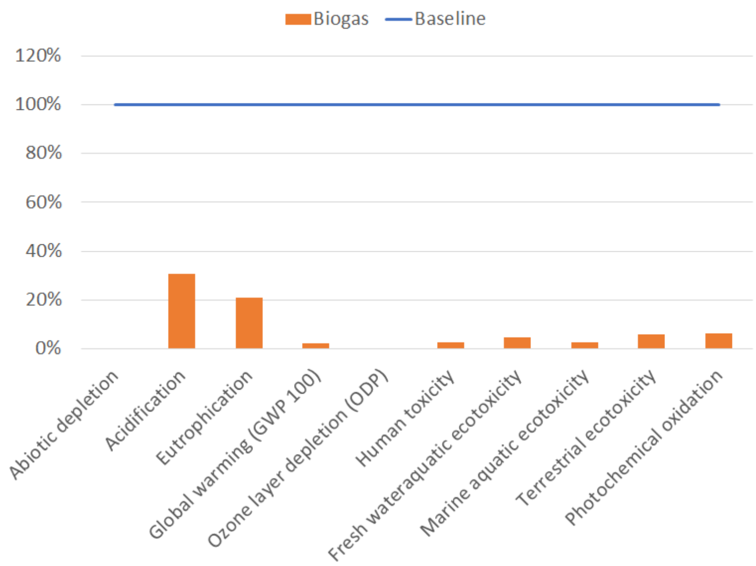

FIGURE F.3: Environmental performance of biogas on the selected KPIs related to the baseline impact in the year 2015

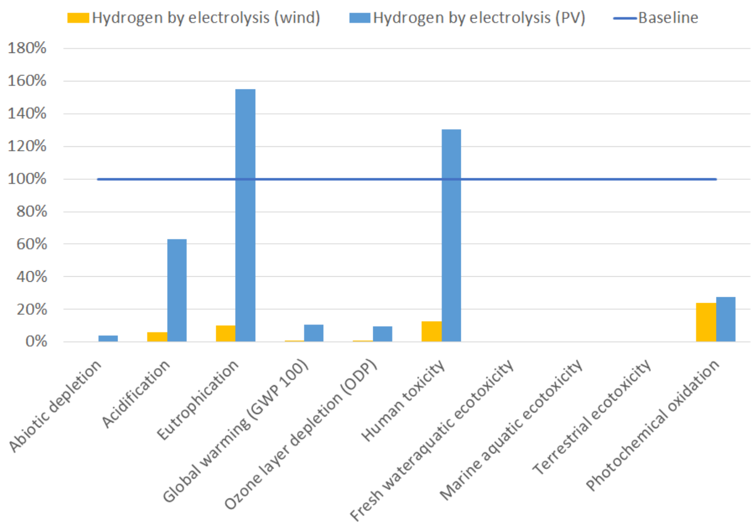

FIGURE F.4: Environmental performance of hydrogen on the selected KPIs related to the baseline impact in the year 2015

Appendix G

Background information of DHN

G.1 District heat technologies

Delivering heat to households using a distinct heat network is not a new technique. The DHN of Copenhagen for example originates from 1984 and covers 97% of the total thermal requirements in the city (Bloomberg, 2011). This DHN is supplied by five CHP plants and four WtE plants supported by 50 oil and gas fueled peak boilers (Dyrelund, 2012, p. 2). The annual heat production in Copenhagen by power plants reach altogether a capacity of 61.4 PJ, wile the support boilers have a combined capacity of 41.0 PJ (CTR, 2004, p. 10).

The resources used to heat the water in the DHN determine whether the thermal energy delivery is sustainable. Significant part of the heating in the Netherlands takes place by natural gas combustion and could therefore be improved on its sustainability.

G.1.1 Types of district heat

In order to identify the best suited neighborhoods and energy production technologies to connect to the DHN, it is important to understand which parameters are essential in the network. There are two types of DHN systems which can be divided into direct and indirect connected systems. The DHN of the direct connected systems contain no physical separation systems such as heat exchangers. Therefore, these networks systems have limitations e.g. the fluid in the system requires equal pressures and temperatures between end users and suppliers (Jaćimovic et al., 1998, p. 318). In this case the heated fluid in the radiators is the same as in the DHN. The indirect connected systems contain different operation systems, separated by heat exchangers. Therefore, varying pressures and temperatures in different levels of the DHN are possible (Eliseev et al., 2011, p. 8).

The most common DHN system in the Netherlands is the indirect-connected system, delivering heat originating from a single supplier, often a CHP plant. In these systems the sources that produce the thermal energy are first transfered with a heat exchanger to a transfer fluid. In most cases, water is used as transfer fluid. The water is subsequently transported through pressurized pipelines. These pipelines transport the heat to the different end users. The end users consume this heat as space- and tap water after which the water returns with a lower temperature to the suppliers. In order to sustain this cycle the supplier has to reheat the temperature of the water with an equal amount of heat as is taken by the end users. The water has to have a certain temperature in order to be useful for the end users. Therefore, it is important to reduce the length of the pipelines as much as possible to minimize the thermal losses. Neighborhoods closer to the supply sources are accordingly prioritized over distant neighborhoods to limit the heat losses.

However, before the heat arrives at the end users it has to pass multiple units and grid levels. According to Skagestad and Mildenstein (2002, p. 56) the delivery of heat can be subdivided into three different main supply and distribution components; the heat supply sources, the distribution grid and end user interfaces. The three different components have a considerable influence on how the network of the district heat supply is designed. Therefore, they will be further elaborated in subsection G.1.2.

G.1.2 Design principles of district heat networks

When designing a district network the different components and characteristics required in the system are essential to be well acquainted. The pressures and temperatures within the pipelines for example can disclose at what level of the grid a proposed technology need to be attached. The different design parameters will be discussed based on the three supply and distribution components, given in subsection G.1.1.

Heat supply sources can be divided into the base-load power plants and peak-load power plants. Whether a technology is used as base-load or peak load supplier is determined using a priority rank. Often the technologies with a high cost efficiency are prioritized on this ranking and used to serve the base load supply. Technologies such as gas or oil based heating boilers which are generally more expensive and often more flexible are used during peak hours.

The type of technologies used and their efficiencies are furthermore closely related on the return temperature of the water (Skagestad and Mildenstein, 2002, p. 56). Low temperature return water is able to absorb more heat than hot water. Likewise, heating of this water can be performed by low grade heat sources. These are heat sources which contain temperatures that are to low to use for electricity generation. Additionally, the return water temperature determines the efficiencies of the CHP plants. When a CHP plant is connected to a DHN the plant is consistently cooled with the return water of the DHN. General guideline of power plant efficiencies indicate that the lower the cooling temperature the higher the power plants efficiency (Borgnakke and R. Sonntag, 2008, p. 424). Return water of DHNs in the Netherlands are commonly about 40°C (Velde, 2017).

Lastly, the technologies used and capacities required depend on the customer demand. The user demand is dynamic and linked to the outside temperature and is furthermore closely related to the sector which consume the heat. The year the building is build plays a major role in the annual consumption (Folkert and Wijngaart, 2012, p. 50). Therefore, district heat supply systems have to deliver more heat to old city centers compared to recently build apartments. The prospected annual demand of the AMA which determines the requirements of the DHN will be further elaborated in chapter 6.

The ***distribution grid*** can be summarized by three different grid network levels: The transmission network, the primary grid and the secondary grid. In every grid level different temperatures, flows and pressures prevail. The DHN within the AMA is an indirect connected system, which means that it operates with higher temperatures (Finney et al., 2013, p. 4). All grid levels distribute heat through pressurized pipelines powered by circulation pumps. The pumps have to be strong enough to surpass the flow resistance arising in the supply- and return pipes and the differential pressure created due ramifications onto consumer heat exchangers. The energy required for these pumps have effects on both the electricity demand and the environmental impact profile of the DHN.

The *transmission network* distributes pressurized high temperature water over large distance. This grid connects all power plants within different geographical areas. Especially district heat networks that cover entire metropolitan areas require a transmission network. The high temperature difference in indirect systems allows lower flow rates and larger pipe diameters. The temperature within this type of grid pipes is commonly 140°C (Finney et al., 2013, p. 4).

The *primary grid* transports the heat to different neighborhoods. The primary grid is generally the most complex network. This mainly occurs due the adoptions the grid has to make to the urban infrastructure. It has to take multiple obstacles into account while minimizing the length to reduce the installation cost and heat loss. The temperature of this grid level is only a little higher than the secondary grid (Skagestad and Mildenstein, 2002, p. 60) and is approximately 120°C.

The *secondary grid* is the final grid which brings the heat energy to the end users. The temperature delivered to the end users can vary as a result of the outside temperature. In order to be useful the supply temperature is 90°C at an outside temperature of -10°C, when the outside temperature is 5°C or higher a supply temperature of 70°C is maintained (Eneco, 2011, p. 8). The optimal flow rate of the hot fluid is 1.3 m/s (Phetteplace, 1995, p. 26) with a common connection quantity of approximately 250 end users (Miltenburg, 2016, p. 15).

General trends in the heat distribution reveal that grid operators try to decrease the supply temperature as much as possible to ensure a reduction of the energy consumption and environmental impact. This can be realized by improved housing insulation and heat exchanger designs. Also, the temperature fluctuations are controlled by either adjusting the supply temperature or the flow rate (Skagestad and Mildenstein, 2002, p. 58). The thermal losses mostly occur within the distribution network and depends on both the length and diameter of the network. General heat losses in the distribution grid are 25W per meter (Törnros et al., 2016, p. 5). And is according to van der Velde (2017) approximately 5 to 10% in the AMA. The lifetime of a district heat pipe is approximately 75 year with an average supply heat of 110°C, using lower supply heat will drastically increase the lifetime of the network (Skagestad and Mildenstein, 2002, p. 59-60).

The ***user interfaces*** can be described by the heat transfer stations which hydraulically separates the different grids and heat transfer fluids using heat exchangers. With the user interface the management of the flows, pressures and temperatures of the grid takes part. The heat exchangers are required to separate all grid levels and manage the heat supply within the end user buildings. The supply flow and pressure can either be managed with valves or pumps. The heat control is managed by the DHN operator but controlled by the end users, who determine the amount of heat required. The design of the interface system is often challenging. It has to be flexible enough to adopt to changes of different buildings. Also, the quality of the interfaces determine the overall efficiency of the DHN. The heat exchangers that separate the different grid levels (Figure G.1) give the DHN operators this flexibility to maintain the right temperature conditions.

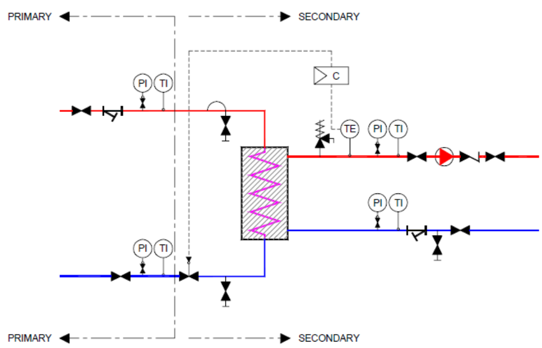

FIGURE G.1: Schematic indirect connection interface between primary and secondary grid with heat exchanger (Skagestad and Mildenstein, 2002)

The target temperatures of the heat exchangers are designed to manage the peak demand in winter circumstances. The temperature of the return flow should be as low as possible. Also, the supply/ return ratio of the radiators of the end users should be guaranteed. Decreasing this supply/ return flows as low as possible is currently carried out in Denmark, where low temperature networks deliver heat with a 55/25°C ratio (Li and Svendsen, 2013, p. 291-292). By lowering the supply and return temperatures the network will become more energy efficient and reduces the environmental impact, and besides will lead to better efficiencies within the suppling power plants. In the Netherlands the radiators generally operate at a supply/ return water temperature of 90/70°C, currently in modern networks this is lowered to 70/40°C (Roos and Manussen, 2011, p. 7). To maintain these temperatures, ideally, the temperature in the primary supply grid is 105°C which eventually should lead to a supply heat temperature of 70°C in the secondary grid. Ideally, the return temperature of the secondary grid is 40°C leading to a return temperature of 42°C in the primary grid. Observations in excising DHNs however turn out that realistic return temperatures are higher. Here a supply temperature of 105°C in the primary grid lead to a temperature of 85°C in the secondary grid, leading to return temperatures of 65°C and 67°C in the secondary and primary grid respectively (Skagestad and Mildenstein, 2002, p. 67). This means that the power plants deliver to much heat which causes unnecessary combustion of resources, leading to higher emissions.

The control of the supply temperature is managed based on the return flow temperature. When the return flow start to increase less heat is required by the end user. Through suppressing the primary grid using valves less thermal heat is transported to the secondary grid which lead to lower supply and return water temperature. Idem, the secondary grid contain control valves (Figure G.2). These valves work the other way around. In cases the supply heat is to low the valve is opened. Opening this valve creates a strong flow towards the return network (Miltenburg, 2016, p. 19).

Also, inside the buildings changes need to be made when connected to a DHN. The boilers which currently manage the heat supply within the buildings will be replaced by heat exchangers when

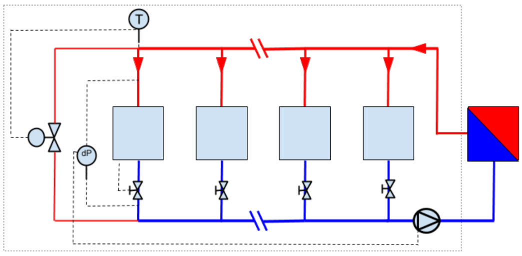

FIGURE G.2: Schematic indirect connection interface between secondary grid and end users with heat exchanger (Miltenburg, 2016)

shifting to a DHN. In some buildings the hot district heat fluid flows directly through the radiators for space heating. The domestic hot water supply is however always separated by a heat exchanger. Often both space heating and hot tap water are separated by two heat exchangers (Figure G.3). This system will always require an extra pump. Nevertheless, this system is regularly more efficient because returning space heat water can preheat the domestic hot water. This way the district heat return water will be colder, while the tap water is preheated (Skagestad and Mildenstein, 2002, p. 75). When shifting to a low temperature supply network buildings should adapt to large area heating such as floor and wall heating.

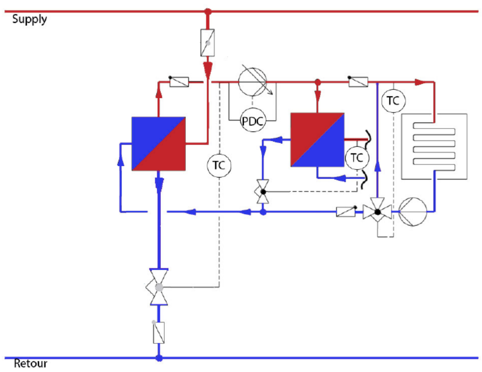

FIGURE G.3: Schematic indirect connection interface between secondary grid and end users with heat exchanger (Miltenburg, 2016)

Appendix H

High density Neighborhoods

TABLE H.1: Neighborhoods with highest heat densities, ordered from highest to lowest densities

Code	Neighborhood name	Amount of residents	MJ	MJ/m^2
BU03630001	Oude Kerk e.o.	1937	125928683	806
BU03630702	Leidsebuurt Noordoost	895	73325089	705
BU03630002	Burgwallen Oost	1125	81364776	665
BU03630003	Nes e.o.	382	49271025	505
BU03630103	Spuistraat Noord	598	47686652	497
BU03630104	Nieuwe Kerk e.o.	640	70173576	494
BU03630700	Leidsebuurt Noordwest	236	23735565	493
BU03630305	Reguliersbuurt	355	37599017	490
BU03630404	Nieuwmarkt	1207	57918273	482
BU03632403	Hercules Seghersbuurt	1934	67519718	473
BU03630602	Bloemgrachtbuurt	2093	100410773	468
BU03632002	Cremerbuurt Oost	1438	51972503	447
BU03630600	Driehoekbuurt	1951	79732958	445
BU03630606	Elandsgrachtbuurt	3395	150100813	428
BU03632501	Van der Helstpleinbuurt	2646	98536528	428
BU03631403	Fannius Scholtenbuurt	2724	79976158	427
BU03630106	Begijnhofbuurt	420	50826137	426
BU03630611	Anjeliersbuurt Zuid	2046	84226488	417
BU03630610	Anjeliersbuurt Noord	1436	69055311	414
BU03634702	Concertgebouwbuurt	1068	91703771	412
BU03633101	Noordwestkwadrant Indische buurt Zuid	2937	100096247	407
BU03630706	Utrechtsebuurt Zuid	868	46522982	401
BU03630300	Spiegelbuurt	693	63046692	396
BU03632000	Helmersbuurt Oost	1451	74480846	392
BU03630203	Leidsegracht Noord	539	45397542	389
BU03632100	Cremerbuurt West	3605	134356927	387
BU03630101	Hemelrijk	449	40971960	386
BU03630306	Leidsegracht Zuid	413	44351481	383
BU03630704	Weteringbuurt	1601	87542843	381
BU03634703	Cornelis Schuytbuurt	1567	125322035	381
BU03630200	Langestraat e.o.	1083	78089007	375
BU03634202	Orteliusbuurt Midden	1155	38613249	375
BU03630000	Kop Zeedijk	656	50858212	374
BU03631801	Bellamybuurt Zuid	2738	103153188	373
BU03630502	Haarlemmerbuurt West	1722	73274585	370
BU03630201	Leliegracht e.o.	1240	107395077	367
BU03632404	Sarphatiparkbuurt	3665	139689156	364
BU03632402	Frans Halsbuurt	1864	73863331	360
BU03630904	Czaar Peterbuurt	1977	64952062	357

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Table H.1 – continued from previous page

Code	Neighborhood name	Residents	MJ	MJ/m^2
BU03631900	Da Costabuurt Zuid	1685	53180874	356
BU03630501	Haarlemmerbuurt Oost	995	60409048	353
BU03631305	Spaarndammerbuurt Noordwest	1582	71140927	353
BU03631601	Frederik Hendrikbuurt Zuidoost	2208	74341291	353
BU03637501	Filips van Almondekwartier	747	26699025	351
BU03632503	Cornelis Troostbuurt	2261	91503267	346
BU03630202	Felix Meritisbuurt	1591	117346992	342
BU03630403	Lastage	873	44848784	342
BU03633001	Transvaalbuurt Oost	2883	115086264	342
BU03634100	John Franklinbuurt	1220	43256146	342
BU03634102	Orteliusbuurt Noord	759	24557910	341
BU03634001	Trompbuurt	1655	70800446	340
BU03634101	Jan Maijenbuurt	1304	44925350	340
BU03632401	Gerard Doubuurt	1462	60719915	338
BU03632802	Oosterparkbuurt Zuidoost	2066	89779550	337
BU03632803	Oosterparkbuurt Zuidwest	2023	69100539	336
BU03634601	Valeriusbuurt West	1298	79792079	335
BU03630102	Nieuwendijk Noord	363	37267821	334
BU03632500	Willibrordusbuurt	1665	69445241	332
BU03634200	Balboaplein e.o.	1874	67016752	330
BU03634500	Schinkelbuurt Noord	1438	60164897	330
BU03634709	Duivelseiland	935	34311149	330
BU03630105	Spuistraat Zuid	498	36880212	325
BU03631404	Westerstaatsman	1830	55055048	325
BU03631902	Lootsbuurt	1277	40807892	325
BU03632602	Burgemeester Tellegenbuurt West	1402	56109902	325
BU03632400	Hemonybuurt	1622	76537974	324
BU03633803	Robert Scottbuurt Oost	979	37480810	323
BU03630302	Van Loonbuurt	943	83174378	321
BU03630303	Amstelveldbuurt	1035	79884681	320
BU03630604	Zaagpoortbuurt	769	20344650	318
BU03634701	P.C. Hooftbuurt	642	61233643	318
BU03631304	Spaarndammerbuurt Midden	785	30618651	316
BU03634705	Hondecoeterbuurt	997	66948804	315
BU03634002	Pieter van der Doesbuurt	1023	38976590	308
BU03630607	Passeerdersgrachtbuurt	614	28416059	307
BU03634402	Aalsmeerwegbuurt West	1501	54350663	306
BU03630407	Zuiderkerkbuurt	874	46869477	305
BU03634404	Legmeerpleinbuurt	906	38952006	305
BU03633100	Noordwestkwadrant Indische buurt Noord	2527	89375235	301
BU03631800	Bellamybuurt Noord	1473	55709175	300
BU03632101	Vondelparkbuurt West	1224	51764613	299
BU03632601	Burgemeester Tellegenbuurt Oost	1530	61268005	299
BU03630107	Kalverdriehoek	347	30364196	298
BU03630505	Planciusbuurt Noord	301	12029969	295
BU03634300	Paramariboplein e.o.	2103	84729032	293
BU03631700	Da Costabuurt Noord	3030	126881684	291
BU03635202	Scheldebuurt Midden	1589	78575513	291
BU03634602	Willemsparkbuurt Noord	891	92517147	290
BU03631301	Spaarndammerbuurt Noordoost	1694	54400253	288
BU03633201	Zuidoostkwadrant Indische buurt	1952	67777303	286
BU03637500	Kortenaerkwartier	1071	47868832	285
BU03631901	Borgerbuurt	1784	59853537	284
BU03632900	Dapperbuurt Noord	2660	100306423	282

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Table H.1 – continued from previous page

Code	Neighborhood name	Residents	MJ	MJ/m^2
BU03631400	De Wittenbuurt Noord	960	35387210	281
BU03632502	Lizzy Ansinghbuurt	1475	60469751	281
BU03631300	Zeeheldenbuurt	1296	48887145	280
BU03635403	Rijnbuurt West	1073	37374562	279
BU03921001	Generaalsbuurt	923	49165234	278
BU03634201	Columbusplein e.o.	1990	72653448	278
BU03634904	Minervabuurt Midden	1131	69941173	276
BU03634600	Valeriusbuurt Oost	711	55916678	275
BU03632200	Vondelparkbuurt Oost	544	59697066	272
BU03635200	Wielingenbuurt	1489	69249484	272
BU03630304	Rembrandtpleinbuurt	396	35156917	271
BU03631405	Buyskade e.o.	1815	59695870	271
BU03632201	Vondelparkbuurt Midden	492	41421398	269
BU03920102	Binnenstad	1660	121184636	267
BU03632901	Dapperbuurt Zuid	2089	78345853	266
BU03633200	Noordoostkwadrant Indische buurt	3327	119917039	266
BU03633102	Zuidwestkwadrant Indische buurt	1976	71497269	265
BU03633000	Transvaalbuurt West	2237	79742313	264
BU03920105	Vijfhoek	1743	109589580	261
BU03920106	Heiliglanden	876	56286948	260
BU03634203	Orteliusbuurt Zuid	1023	36705312	260
BU03631303	Spaarndammerbuurt Zuidwest	1033	32972895	258
BU03635300	IJselbuurt West	1546	57904803	258
BU03632600	Diamantbuurt	1744	71795511	255
BU03634805	Van Tuyllbuurt	2330	90190195	254
BU03630603	Marnixbuurt Noord	1026	30848733	253
BU03634403	Aalsmeerwegbuurt Oost	1312	50198282	252
BU03634802	Marathonbuurt West	1526	51565129	252
BU03632001	WG-terrein	1527	70442943	249
BU03634400	Surinamepleinbuurt	734	37060916	246
BU03633706	Landlust Noord	1508	40637916	245
BU03634700	Johannnes Vermeerbuurt	792	66172144	245
BU03635203	Scheldebuurt Oost	1263	58052974	245
BU03632800	Oosterparkbuurt Noordwest	2545	90368260	243
BU03633704	Erasmusparkbuurt Oost	984	37294972	243
BU03634704	Banpleinbuurt	452	45649535	241
BU03630004	BG-terrein e.o.	493	40979592	239
BU03634401	Westlandgrachtbuurt	2050	75719533	239
BU03635600	Linnaeusparkbuurt	1314	71845558	239
BU03630907	Kazernebuurt	680	26239634	235
BU03920104	Burgwal	1690	84189208	235
BU03635201	Scheldebuurt West	2290	100930620	234
BU03635301	IJselbuurt Oost	1535	62764347	234
BU03634000	Geuzenhofbuurt	1029	36532029	231
BU03634800	Bertelmanpleinbuurt	622	23147171	230
BU03631401	De Wittenbuurt Zuid	566	17875856	229
BU03631600	Frederik Hendrikbuurt Noord	2401	81766136	228
BU03750004	Sint Aagtendorp	396	24064159	226
BU04730206	Centrum	1330	104118992	226
BU03920103	Bakenes	1332	96042025	225
BU03630703	Leidsebuurt Zuidoost	224	19089151	221
BU03633703	Landlust Zuid	2650	80757319	221
BU03633705	Gibraltarbuurt	2302	74723132	221
BU19420004	Cereslaan	613	37068161	221
BU03637502	De Wester Quartier	791	28891206	221

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Table H.1 – continued from previous page

Code	Neighborhood name	Residents	MJ	MJ/m^2
BU03635601	Middenmeer Noord	1226	68481758	219
BU03920702	Potgieterbuurt	958	44955385	217
BU03920205	Rozenprieel-zuid	1016	50290674	216
BU03921004	Frans Halsbuurt	836	47682467	216
BU03634301	Postjeskade e.o.	1712	64102636	216
BU03637503	Van Brakelkwartier	509	18864028	209
BU03630705	Den Texbuurt	567	39137352	205
BU03920304	Leidsebuurt-oost	1051	57905541	205
BU03632700	Swammerdambuurt	1125	48708129	205
BU04020102	Havenstraatbuurt	1285	78961187	205
BU03630605	Marnixbuurt Midden	149	7450871	204
BU03631402	Staatsliedenbuurt Noordoost	787	23387664	203
BU03634905	Minervabuurt Zuid	1210	55342071	202
BU03921401	Nachtegaalbuurt	1035	52639045	201
BU03920303	Leidsebuurt-west	1281	59445987	199
BU03750005	Reguliersstraat	486	25264792	197
BU03631302	Spaarndammerbuurt Zuidoost	492	18773711	196
BU03635503	Don Bosco	1089	53441519	195
BU19420000	Brinklaan	1018	71421372	195
BU03920302	Hasselaersbuurt	630	40055430	193
BU03630701	Leidsebuurt Zuidwest	129	10491106	191
BU03630301	Gouden Bocht	120	17680311	189
BU03630801	Sarphatistrook	1216	68335662	189
BU04020104	Langgewenstbuurt	993	65547842	189
BU03921306	Burgemeesterskwartier	561	35063928	188
BU04020401	Bloemenkwartier Noord	1285	86441706	188
BU03630800	Weesperbuurt	1870	88000686	187
BU03920201	Koninginnebuurt	1284	102082508	186
BU03921101	Medanbuurt	829	43617659	186
BU03632701	Weesperzijde Midden/Zuid	1666	73937294	185
BU03635400	Kromme Mijdrechtbuurt	1480	57693431	185
BU03630707	Frederikspleinbuurt	713	48436160	184
BU19420003	Batterijlaan	500	35437504	183
BU19420008	Spiegelzicht	503	46683920	183
BU03634706	Harmoniehofbuurt	722	34929332	182
BU03750002	Koningstraat	1003	49304788	181
BU04020101	Centrum	1913	121086301	181
BU03920204	Rozenprieel-noord	651	30832238	180
BU03920301	Garenkokerskwartier	912	59683033	178
BU03750300	Plantage	1064	49114026	176
BU03630901	Kattenburg	728	35854444	176
BU03633702	Bosleeuw	2502	101566916	176
BU03634903	Minervabuurt Noord	546	42701339	176
BU03630908	Kadijken	1833	63747278	173
BU04530103	Verzetsheldenbuurt	880	47723475	172
BU03920701	Oude Amsterdamsebuurt	1349	56903091	171
BU19420202	Godelindebuurt	502	25892190	170
BU04530204	Paterskerkbuurt	439	19574321	169
BU19420001	Raadhuisplein	871	57507065	169
BU03638806	BelgiÃ«plein e.o.	631	23643701	169
BU03630503	Westelijke eilanden	1433	61499388	168
BU03921402	Meeuwenbuurt	496	26524792	168
BU04390101	Binnenstad	1303	88363113	167
BU03921002	De Goede Hoop	993	49359583	167
BU04020302	Het Rode Dorp	571	35649543	167

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Table H.1 – continued from previous page

Code	Neighborhood name	Residents	MJ	MJ/m^2
BU03634901	Beethovenbuurt	472	42756873	166
BU03921207	Kleverpark-zuid	1058	73885453	165
BU04570002	Herensingelkwartier	517	26925414	164
BU03921201	Bomenbuurt-west	911	48542865	164
BU03921604	Muiderkring	572	33500129	164
BU03921605	Van Aemstelbuurt	500	25877629	164
BU03633902	Kolenkitbuurt Zuid	848	35550892	164
BU03636101	Vogelbuurt Zuid	1926	94923795	164
BU03630405	Uilenburg	746	29461136	163
BU03630609	Marnixbuurt Zuid	396	14034765	162
BU03634900	Diepenbrockbuurt	529	60485753	162
BU03630408	Waterloopleinbuurt	681	35288453	161
BU03921305	Planetenbuurt	619	35207316	160
BU03920703	Cremerbuurt	611	25480701	159
BU03750302	Kuenenplein	923	41226345	158
BU03920704	Van Zeggelenbuurt	1093	53037205	156
BU19420002	Verbindingslaan	603	34779297	156
BU19420005	Bijlstraat	504	30492179	156
BU19420100	Prins Hendrikkwartier	288	36512439	155
BU04020601	Geuzenbuurt	1231	72201091	155
BU03631602	Frederik Hendrikbuurt Zuidwest	633	21931485	154
BU03633802	Erasmusparkbuurt West	2250	87225926	154
BU03630608	Groenmarktkadebuurt	151	12745925	153
BU04530602	West-Indische buurt	347	18600921	152
BU03630902	Wittenburg	1238	46452712	152
BU03633307	Architectenbuurt	1116	36111959	150
BU03750101	Ronde Boogaard	1149	75576427	148
BU04791130	Burgemeestersbuurt	3158	175168019	148
BU03921103	Weltevredenbuurt	834	42421843	148
BU03635602	Middenmeer Zuid	2352	98884430	148
BU03635401	Rijnbuurt Oost	1480	57662271	147
BU03920801	Kruistochtbuurt	1093	50842069	146
BU03970000	Centrum	1960	117339536	146
BU04020402	Bloemenkwartier Zuid	2308	143738243	146
BU09956662	Neringpassage	388	21906303	145
BU04530104	Natuurkundigenbuurt	897	52882105	144
BU04530603	Santpoort-Dorp	355	23734088	144
BU09951661	Bastion	275	14771189	144
BU03637400	Nintemanterrein	100	9489042	144
BU04530105	Kikvorsbuurt	617	29347642	143
BU03921105	Soendabuurt	970	48697930	143
BU03921302	Schotervlieland	361	24924944	143
BU03637703	Buurt 5 Noord	1362	55781273	143
BU03637802	Buurt 8	1459	64813598	143
BU04020103	Sint Vitusbuurt	822	48311165	142
BU04530203	Velseroord	906	38412886	141
BU03750301	Oostertuinen	1040	46311856	140
BU03635402	Rijnbuurt Midden	1361	67581547	140
BU03750303	De Naald	219	10527683	139
BU19420201	Donderstraat	458	36375241	139
BU03630401	Scheepvaarthuisbuurt	337	25138883	138
BU03920803	Karolingenbuurt	1004	45281516	138
BU03921202	Bomenbuurt-oost	665	42009686	137
BU04570202	Schildersbuurt	527	27135484	136
BU03921403	Dietsveld	564	29929741	136

Continued on next page

Table H.1 – continued from previous page

Code	Neighborhood name	Residents	MJ	MJ/m^2
BU04020404	Staatsliedenkwartier	1510	96631017	136
BU03921104	Molukkenbuurt	516	32777913	135
BU03750200	Oranjebuurt	394	19958131	134
BU04792140	Russische buurt	1462	112521105	134
BU03921503	Rivierenbuurt	651	34842075	134
BU03636400	Buiksloterdijk West	86	5998701	134
BU19420102	Vondellaan	536	43821328	134
BU03921603	Roemer Visscherbuurt	862	46473357	133
BU03940553	Badhoevedorp West	720	40866872	133
BU03920402	Zeeheldenbuurt	920	54031707	132
BU03960100	Centrum	951	55399222	132
BU03636300	Blauwe Zand	887	38666039	132
BU03638100	Wildeman	2474	72925031	131
BU03636402	Nieuwendammmerdijk West	410	25910337	130
BU04020602	Electrobuurt	900	50165715	129
BU04020603	Kleine Driftbuurt	1817	100778475	129
BU04170000	Laren-Dorpskern	1050	111467623	129
BU04020202	Raadhuiskwartier	674	97247864	128
BU04530200	Tussenbeeksbuurt	829	49597684	126
BU03920503	Ramplaankwartier	1161	73067891	126
BU04020702	Erfgooiersbuurt	748	45289887	126
BU04792210	Oud West	2294	146606638	125
BU03921003	Nelson Mandelabuurt	469	25425660	125
BU09956664	Stadhuisstraat	437	17556372	125
BU04530106	Stadhuisbuurt	444	25668790	124
BU03850204	Volendam-Blokgouw 3	566	39118923	124
BU03921205	Kleverpark-noord	985	66893270	124
BU03921804	Landenbuurt	1031	43436217	124
BU04061124	Bovenmaat West	729	32229577	124
BU03750001	Meerplein	747	51931073	123
BU03921304	Sinnevelt	1256	59862013	122
BU03921501	Schrijversbuurt	1001	38020775	122
BU19420006	Nijverheidswerf	416	22181086	122
BU03636911	De Kleine Wereld	1178	49175890	122
BU03620003	Elsrijk-West	1993	146998361	121
BU04530605	Kerkerinkbuurt	407	20497006	121
BU03630406	Valkenburg	372	15059970	121
BU03840115	Centrum-West	935	51493628	121
BU03630506	Planciusbuurt Zuid	110	3537786	121
BU04730203	Brederode- Gerkestraat e.o.	1389	94598016	121
BU04020403	Schrijverskwartier	796	66191980	121
BU03840004	Kruidenhof	662	28201417	120
BU03850201	Volendam-Oude kom	2105	139413177	120
BU03636200	Tuindorp Nieuwendam West	566	24309188	120
BU19420208	Midden Eng-West	699	35392697	120
BU03638902	Staalmanbuurt	1069	64982414	120

Appendix I

Sensitivity analysis

TABLE I.1: Sensitivity analysis abiotic depletion

Improvement configuration	**Technology**	**-50%**	**+50%**
BAU	Natural gas	-3.1%	3.1%
	Geothermal	-0.1%	0.1%
	Biogas	0.0%	0.0%
	Biomass	-0.1%	0.1%
	Hydrogen	0,0%	0,0%
	Natural gas Boiler	-18.6%	18.6%
	Natural gas production	-28.2%	28.2%
Realistic	Natural gas	-2.2%	2.2%
	Geothermal	-0.2%	0.2%
	Biogas	0.0%	0.0%
	Biomass	-0.2%	0.2%
	Hydrogen	0.0%	0,0%
	Natural gas Boiler	-20.7%	20.7%
	Natural gas production	-26.7%	26.7%
Optimistic	Natural gas	0.0%	0.0%
	Geothermal	-0.3%	0.3%
	Biogas	0.0%	0.0%
	Biomass	-0.2%	0.2%
	Hydrogen	0.0%	0.0%
	Natural gas Boiler	-26.4%	26.4%
	Natural gas production	-23.1%	23.1%

TABLE I.2: Sensitivity analysis acidification

Improvement configuration	Technology	-50%	+50%
BAU	Natural gas	-3.2%	3.2%
	Geothermal	-1.6%	1.6%
	Biogas	-0.7%	0.7%
	Biomass	-2.1%	2.1%
	Hydrogen	0,0%	0,0%
	Natural gas Boiler	-40.8%	40.8%
	Natural gas production	-1.6%	1.6%
Realistic	Natural gas	-2.0%	2.0%
	Geothermal	-3.1%	3.1%
	Biogas	-1.1%	1.1%
	Biomass	-3.9%	3.9%
	Hydrogen	0.0%	0,0%
	Natural gas Boiler	-38.7%	38.7%
	Natural gas production	-1.3%	1.3%
Optimistic	Natural gas	0.0%	0.0%
	Geothermal	-3.2%	3.2%
	Biogas	-2.9%	2.9%
	Biomass	-3.9%	3.9%
	Hydrogen	-0.1%	0.1%
	Natural gas Boiler	-39.1%	39.1%
	Natural gas production	-0.9%	0.9%

TABLE I.3: Sensitivity analysis global warming

Improvement configuration	Technology	-50%	+50%
BAU	Natural gas	-6.2%	6.2%
	Geothermal	-0.3%	0.3%
	Biogas	-0.1%	0.1%
	Biomass	-0.3%	0.3%
	Hydrogen	0,0%	0,0%
	Natural gas Boiler	-42.4%	42.4%
	Natural gas production	-0.8%	0.8%
Realistic	Natural gas	-4.2%	4.2%
	Geothermal	-0.5%	0.5%
	Biogas	-0.1%	0.1%
	Biomass	-0.5%	0.5%
	Hydrogen	0.0%	0,0%
	Natural gas Boiler	-44.0%	44.0%
	Natural gas production	-0.7%	0.7%
Optimistic	Natural gas	0.0%	0.0%
	Geothermal	-0.6%	0.6%
	Biogas	-0.3%	0.3%
	Biomass	-0.6%	0.6%
	Hydrogen	0.0%	0.0%
	Natural gas Boiler	-26.4%	26.4%
	Natural gas production	-0.6%	0.6%

TABLE I.4: Sensitivity analysis Photochemical oxidation

Improvement configuration	**Technology**	**-50%**	**+50%**
BAU	Natural gas	-2.0%	2.0%
	Geothermal	-0.7%	0.7%
	Biogas	-0.1%	0.1%
	Biomass	-6.2%	6.2%
	Hydrogen	0,0%	0,0%
	Natural gas Boiler	-39.8%	39.8%
	Natural gas production	-1.1%	1.1%
Realistic	Natural gas	-1.1%	1.1%
	Geothermal	-1.3%	1.3%
	Biogas	-0.2%	0.2%
	Biomass	-11.1%	11.1%
	Hydrogen	0.0%	0,0%
	Natural gas Boiler	-35.4%	35.4%
	Natural gas production	-0.8%	0.8%
Optimistic	Natural gas	0.0%	0.0%
	Geothermal	-1.3%	1.3%
	Biogas	-0.5%	0.5%
	Biomass	-11.3%	11.3%
	Hydrogen	-0.3%	0.3%
	Natural gas Boiler	-36.0%	36.0%
	Natural gas production	-0.6%	0.6%

Appendix J

Spatial analysis

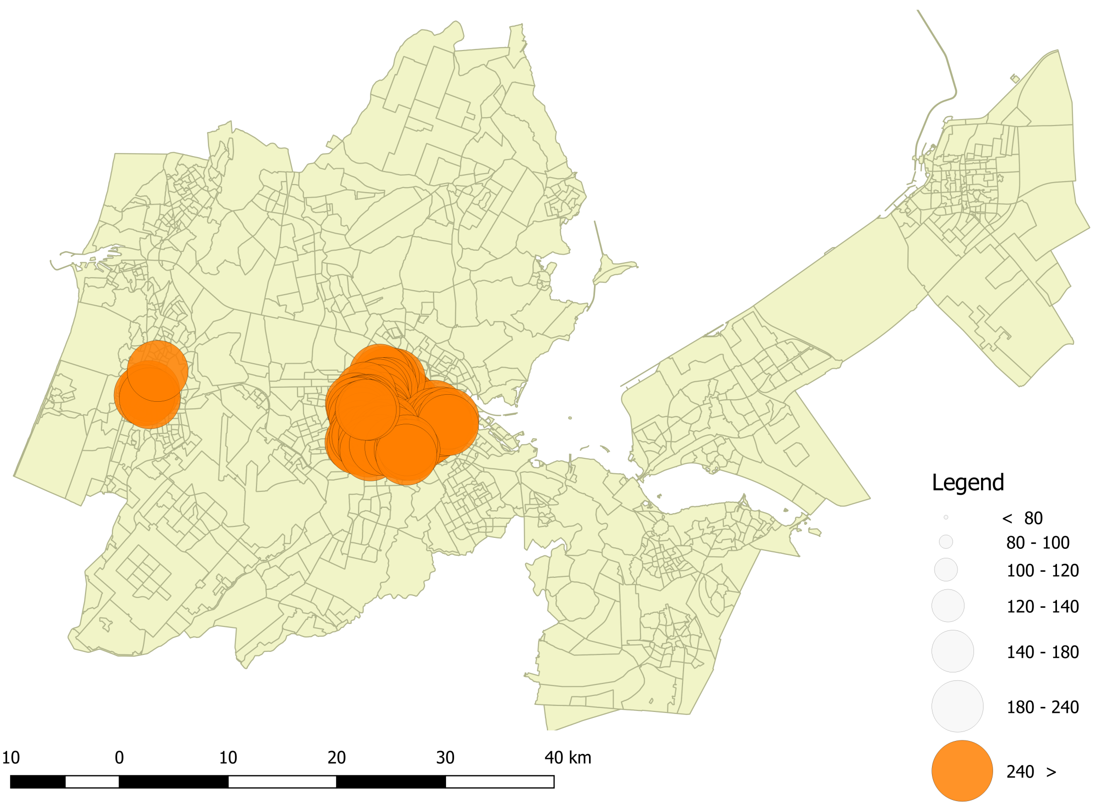

FIGURE J.1:]
Heat density neighborhoods, higher than 240 MJ/m^2

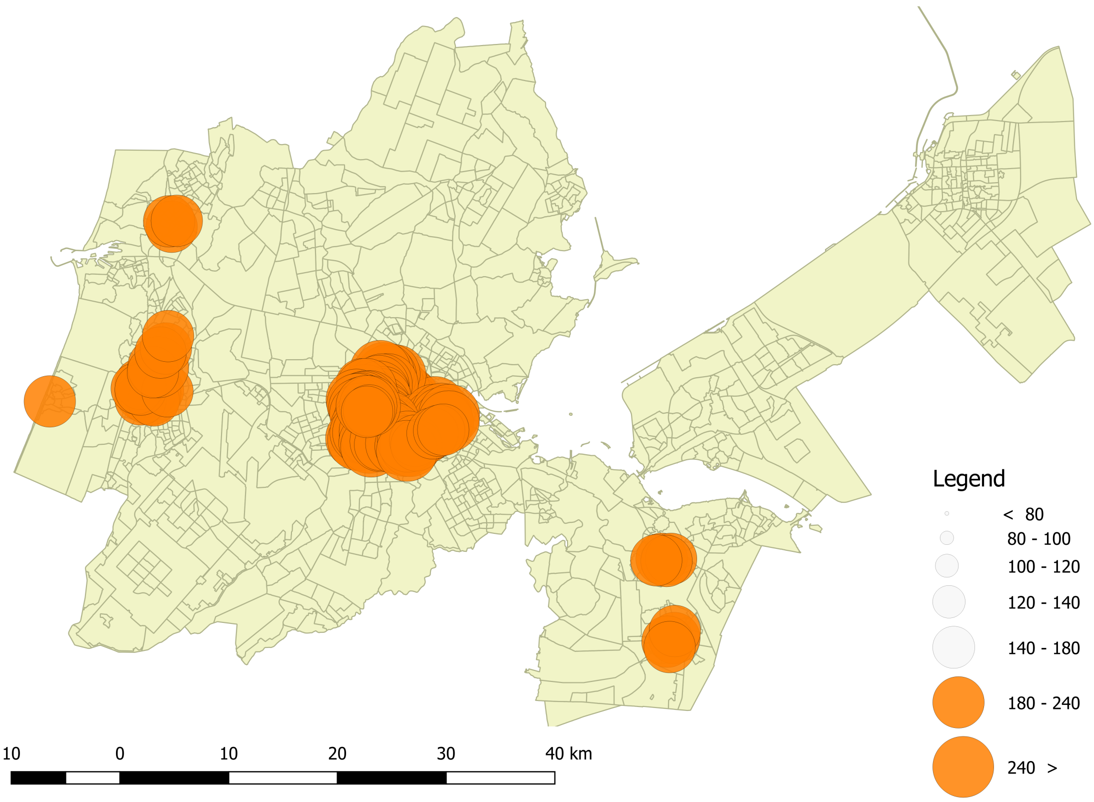

FIGURE J.2:]
Heat density neighborhoods, higher than 180 MJ/m^2

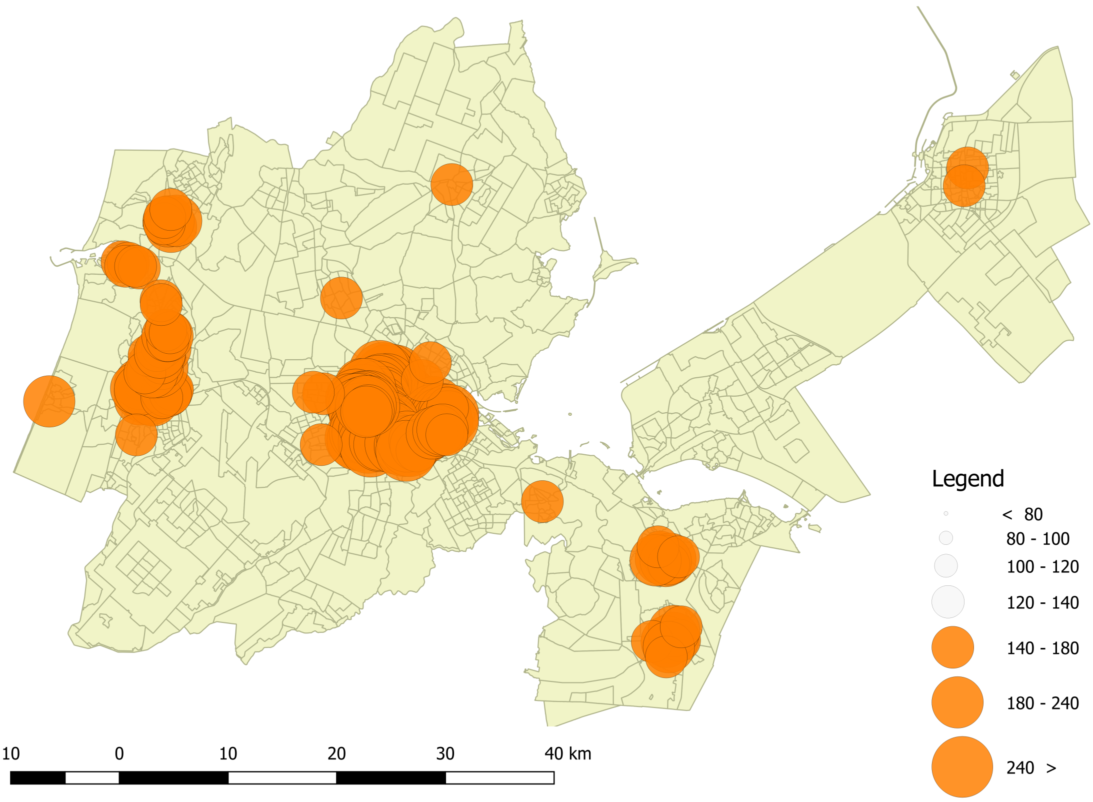

FIGURE J.3:]
Heat density neighborhoods, higher than 140 MJ/m^2

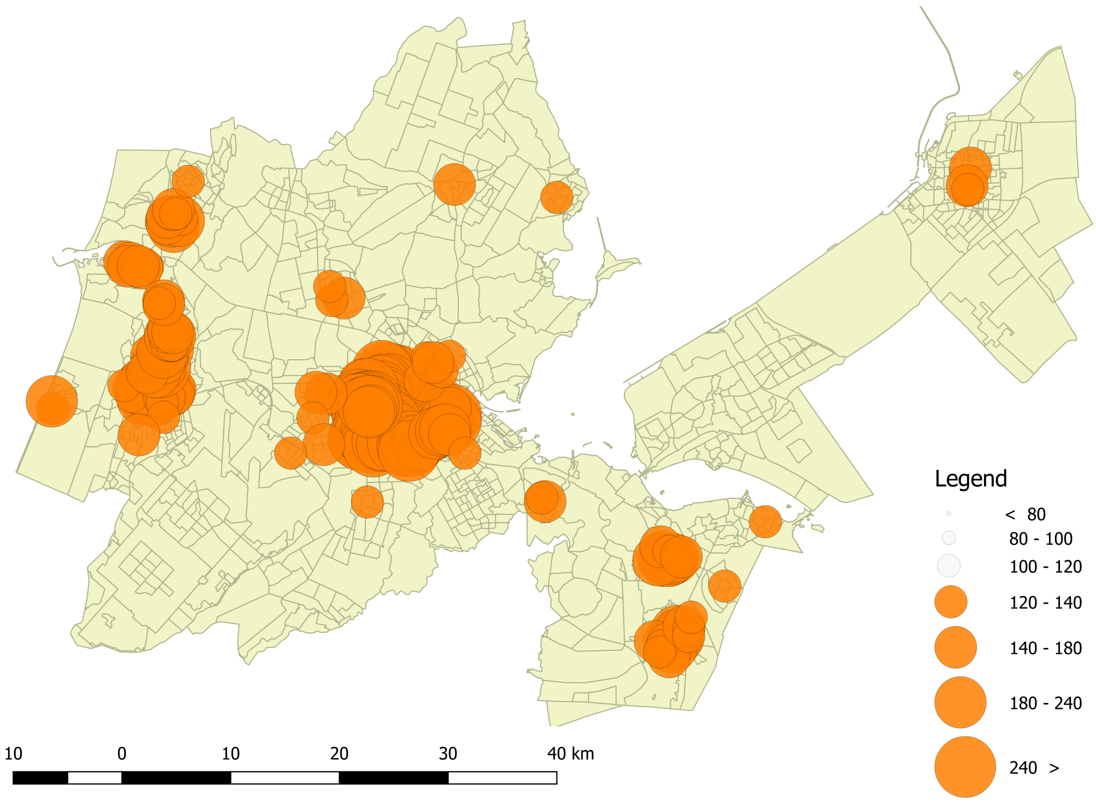

FIGURE J.4:]
Heat density neighborhoods, higher than 120 MJ/m^2

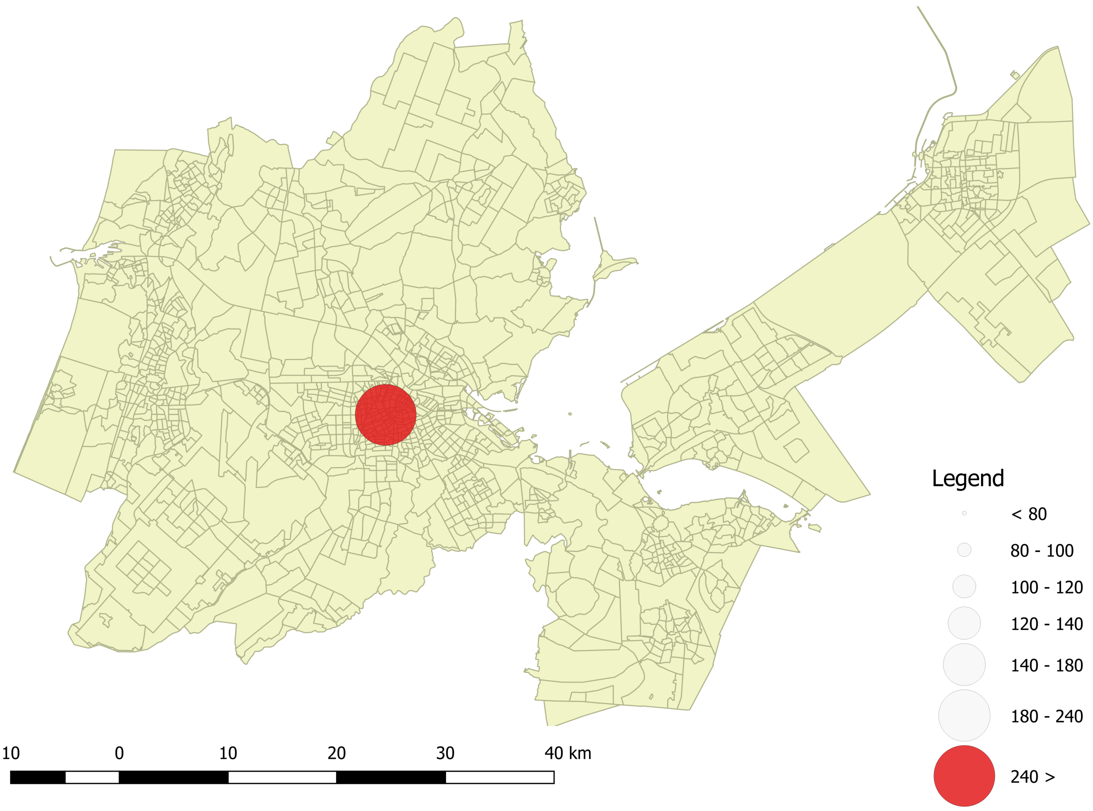

FIGURE J.5:]
Heat density of high population concentration areas, higher than 240 MJ/m^2

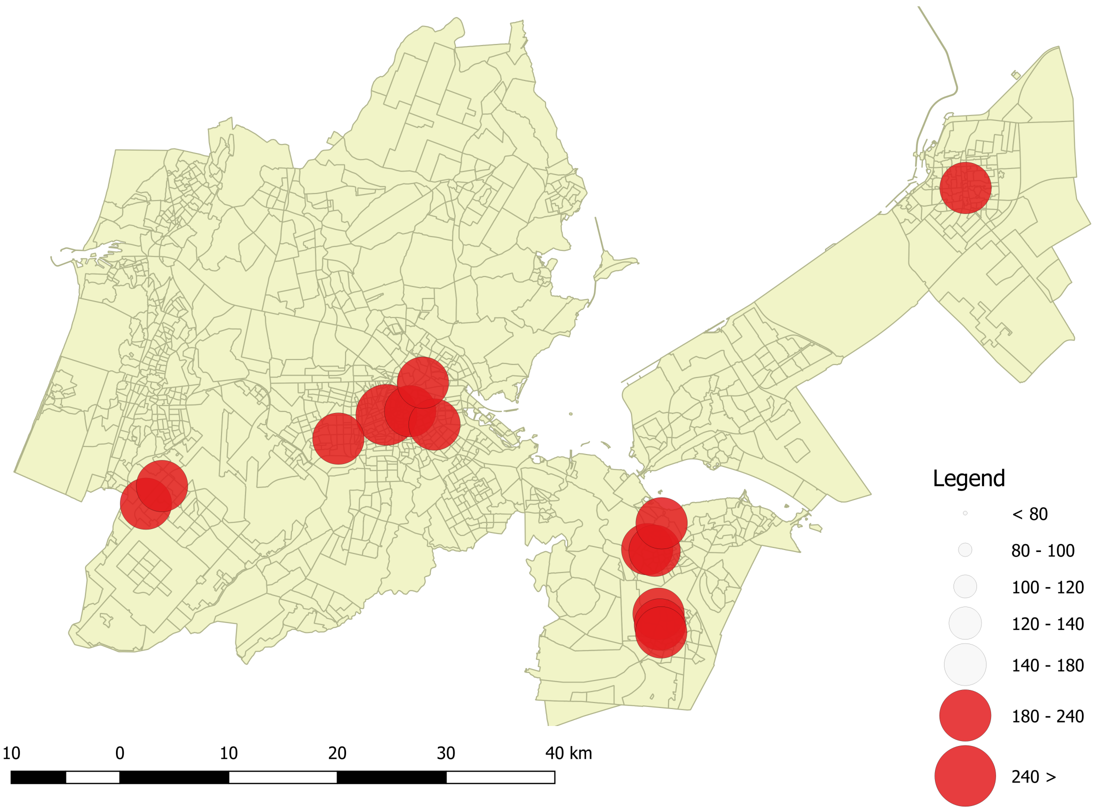

FIGURE J.6:]
Heat density of high population concentration areas, higher than 180 MJ/m^2

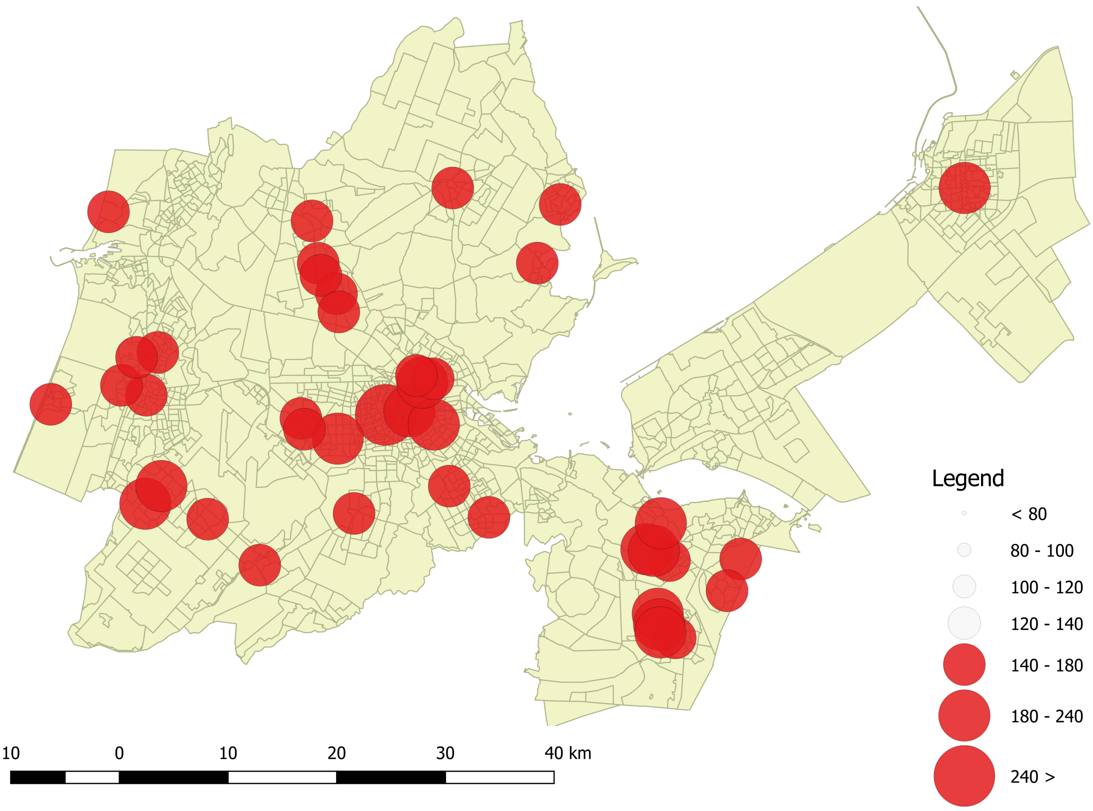

FIGURE J.7:]
Heat density of high population concentration areas, higher than 140 MJ/m^2

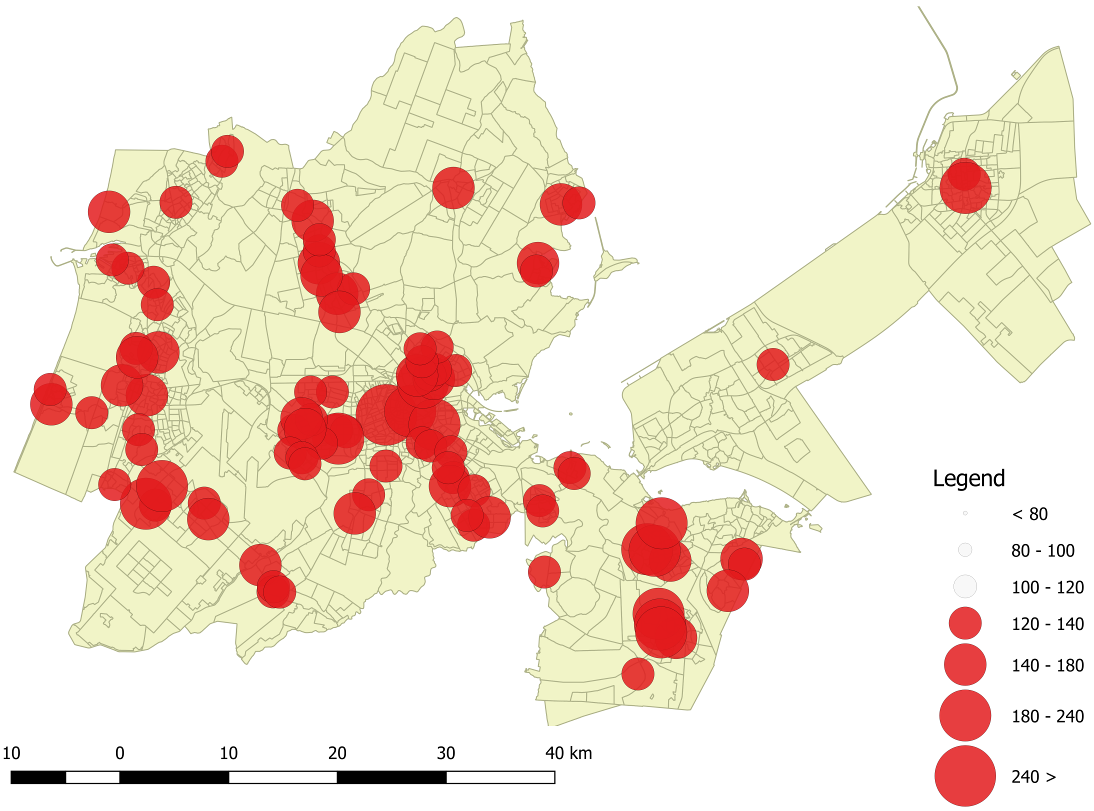

FIGURE J.8:]
Heat density of high population concentration areas, higher than 120 MJ/m^2

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252,268,271,279,356,362,370,439-440,452,470,472,485,492,497,499&D4=5&VW=T (visited on 05/01/2017).
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